Journal of Ethnobiology 22(1): 1–33 Summer 2002

OBSERVATIONAL STUDY OF MAIZE PRODUCTION SYSTEMS OF ZUNI FARMERS IN SEMIARID NEW MEXICO

DEBORAH A. MUENCHRATH,[a] MAYA KURATOMI,[b] JONATHAN A. SANDOR,[a] and JEFFREY A. HOMBURG[c]

[a]*Agronomy Dept.—Crop, Soil, and Environmental Sciences, Iowa State University, Ames, IA 50011-1010*

[b]*Soil Science Dept., 1991 Upper Buford Circle, University of Minnesota, St. Paul, MN 55108*

[c]*Statistical Research, Inc., 6099 E. Speedway Blvd., P.O. Box 31865, Tucson, AZ 85751-1865*

ABSTRACT.—For more than 2,000 years, the Zuni and their ancestors have cultivated maize in semiarid New Mexico, relying on natural landscape processes to channel water and nutrients to their crops. Runoff generated by localized thunderstorms spreads across fields located on alluvial fans. This study documents soil properties, production practices, and maize yields of four traditional runoff fields of Zuni farmers. All fields received at least two runoff events that deposited sediments and organic debris during the season. Fields exhibited adequate macronutrients for low-density crop production and textural sorting of sediments. Management level is largely determined by time, labor, equipment, and transportation availability. Farmers commonly plant during May, sowing multiple maize seeds together at a depth of about 15 cm in widely-spaced clusters. Each field contained two or more open-pollinated maize folk cultivars, sometimes interspersed with other crops. Maize population densities varied widely, averaging 9650 plants/ha (SE ± 1281). Mean grain yield was 572 (± 181) kg/ha. Greatest yield, 1841 kg/ha, was obtained from the field having moderate maize density, few weeds, and planted in mid-May. Delayed planting and weeds suppressed yields in the other fields. Yield potential of these systems, however, is likely greater than observed. Geographic and geomorphic diversity of fields reduces risks.

Key words: indigenous agricultural knowledge, Native American agriculture, runoff agriculture, maize, soil.

RESUMEN.—Durante más de 2000 años, los Zuni y sus ancestros han cultivado maíz en el Nuevo Mexico semiárido, y han manejado cuencas con la finalidad de canalizar el agua y los nutrientes hacia sus cultivos. El escurrimiento superficial generado por las tormentas locales se distribuye a través de los campos ubicados sobre abanicos aluviales. Este estudio documenta las propiedades del suelo, las prácticas productivas, y los rendimientos de maíz en cuatro campos tradicionales de escurrimiento manejados por los agricultores Zuni. Todos los campos presentaron al menos dos fenómenos de escurrimiento durante la estación, los cuales depositaron sedimentos y detritus orgánico. Los campos mostraron macronutrientes adecuados para una producción de cosechas de baja densidad de siembra y un repartimiento de varias clases sedimentarias. La intensidad de manejo la determina principlamente la disponibilidad de tiempo, mano de obra, equipamiento y transporte. La siembra se produce comúnmente en mayo. Los agricultores siem-

bran maíz a una profundidad de unos 15 cm en montículos de múltiples plantas. Cada campo contiene dos o más cultivares tradicionales de maíz de polinización abierta, a veces mezclados entre otros cultivos. Las densidades de población de maíz varían ampliamente en torno a una media de 9650 plantas/ha (SE ± 1281). La producción media de grano fue 572 (± 181) kg/ha. La producción mayor, 1841 kg/ha, se obtuvo en un campo con una densidad poblacional moderada, pocas malezas, y con fecha de siembra de mediados de mayo. El retraso en la siembra y las malezas redujeron la producción en los otros campos. Es posible que el nivel de producción de estos sistemas sea mayor de lo observado. La diversidad geográfica y geomorfológica de los campos reduce los riesgos.

RÉSUMÉ.—Pendant plus de 2000 ans, les Zuni et leurs ancêtres ont cultivé le maïs dans le New Mexico semi-aride, comptants sur des processus du paysage naturel pour canaliser l'eau et les substances nutritives vers leurs cultures. L'eau de ruissellement provenant d'averses locales s'étend sur les champs situés sur des petits deltas alluviaux. Cette étude documente les caractères des sols, les pratiques de production, et le rendement du maïs sur quatre champs appartenants à des agriculteurs Zuni et traditionnellement approvisionés par des ruissellements. Pendant la belle saison, chaque champ a reçu au moins deux épisodes de ruissellement qui déposaient sédiments et débris organiques. Les champs contenaient des micronutriments adéquats pour la culture à basse densité et un triage textural des sédiments. Le niveau des interventions est determiné par la disponibilité de temps, de main-d'œuvre, d'équipement et de transport. En général, les agriculteurs sèment pendant le mois de mai, avec le maïs planté à une profondeur d'à peu près 15 cm en groupes de multiples plantes. Chaque champ contient au moins deux variétés traditionnelles à pollinisation ouverte, parfois intercalées aux autres cultures. La densité des populations du maïs, qui variait considérablement d'un champ à l'autre, était en moyenne de 9650 plantes/ha (déviation d'erreur ± 1281). Le rendement moyen était de 572 (± 181) kg/ha. Le plus haut rendement, de 1841 kg/ha fut réalisé dans un champ avec peu de mauvaises herbes, de densité moyenne, et semé à mi-mai. Une ensemencement tardif et les mauvaises herbes réduisaient le rendement dans les autres champs. Le rendement potentiel de ces systèmes est vraisemblablement plus élevé que nous l'avons observé. La géographie et la géomorphologie diversifiées des champs réduisent les risques.

INTRODUCTION

Worldwide, water is the single most limiting resource for crop production. Increasing demand for water by agricultural and non-agricultural users, environmental deterioration, and the threat of global climate change challenge the long-term sustainability of agriculture and socio-economic development in the arid and semiarid western United States and other drought-susceptible regions of the world (e.g., FAO 2000; Gleick 2000; OTA 1983). Arid and semiarid zones occupy more than a third of the Earth's land surface, with dry regions located in nearly half of the world's nations. Over 80 percent of the world's cultivated land is rainfed, relying solely on precipitation and runoff; these lands produce more than 60 percent of the global food supply (FAO 2000).

Rain could be better utilized to support agricultural productivity through management of storm-runoff water (Anaya 1992; Bruins et al. 1986; Critchley and Siegert 1991; FAO 2000; OTA 1983). Rainwater-harvesting methods have been suc-

cessfully used in traditional systems throughout the world and as part of modern agricultural systems in areas such as the Negev Desert. These water-harvesting methods are particularly applicable to agricultural development in arid and semiarid areas where high capital investment or highly technological systems are environmentally, socially, or economically unsuitable.

A diversity of rainwater-harvesting systems have been used for centuries by the Zuni and their ancestors and other peoples in the arid and semiarid southwestern U.S. and northern Mexico (Bryan 1929; Cushing 1974; Doolittle 2000; Hack 1942; Hart 1995; Maxwell 2000; Nabhan 1984); the Zuni are one of the western Puebloan tribes of the U.S. Southwest. Traditional agricultural systems presently found at Zuni and in other Native American communities in the region provide models of enduring systems. Expanded understanding of their adapted cultivars and the agroecological structure and function of these systems may contribute to the development of sustainable agricultural systems to successfully meet the challenges of increased water demands in arid and semiarid areas.

Most of the available information about traditional Native American agriculture in the U.S. Southwest is based on ethnographies, historical and archaeological records, and agronomic studies focused on modern cultivars and practices or on traditional systems in other regions. Several researchers have used such information to model productivity of ancient and current traditional systems (e.g., Rhode 1995; Van West 1996). Little research, however, has been conducted on specific agronomic characteristics of traditional cultivars and associated practices. Documentation of these time-tested systems is urgent. Traditional agricultural knowledge in the Southwest is rapidly eroding as fewer indigenous farmers apply that knowledge or pass it on to younger generations (Brandt 1995). Commercial production of alfalfa, increasingly important on reservations, also threatens to further displace traditional techniques.

The observational study reported here documents contemporary runoff agricultural practices of several Zuni farmers and explores general relationships among soil properties, production practices, and maize productivity of their fields. This study is part of a larger research project designed to examine the agroecological structure and function of traditional runoff agriculture in this semiarid environment (e.g., Sandor et al. 1999).

Location and Landscape.—The Zuni Indian Reservation is located in the mesa country of western New Mexico in the southeastern part of the Colorado Plateau (Figure 1). Topography is controlled by mainly flat-lying to gently dipping strata of uplifted sedimentary rocks with variable resistance to erosion. Alternating strata of resistant sandstone and more erodible shale of mostly Triassic to Cretaceous age underlie mesas and cuestas (Orr 1987). Mesas are separated by narrow canyons to broad alluvial valleys. Valley margins, where traditional runoff agriculture is usually practiced, mostly comprise areas of coalescing alluvial fans where ephemeral streams deposit mixed sediments from mesa uplands. Soils grade from Alfisols (soils having subsurface clay accumulation) and Aridisols (desert soils with subsurface development) in the drier western portion to Mollisols (soils having thick topsoil rich in organic matter) and Alfisols in the higher eastern valleys of the reservation (Soil Survey Staff 1999; USDA-NRCS, publication pending).

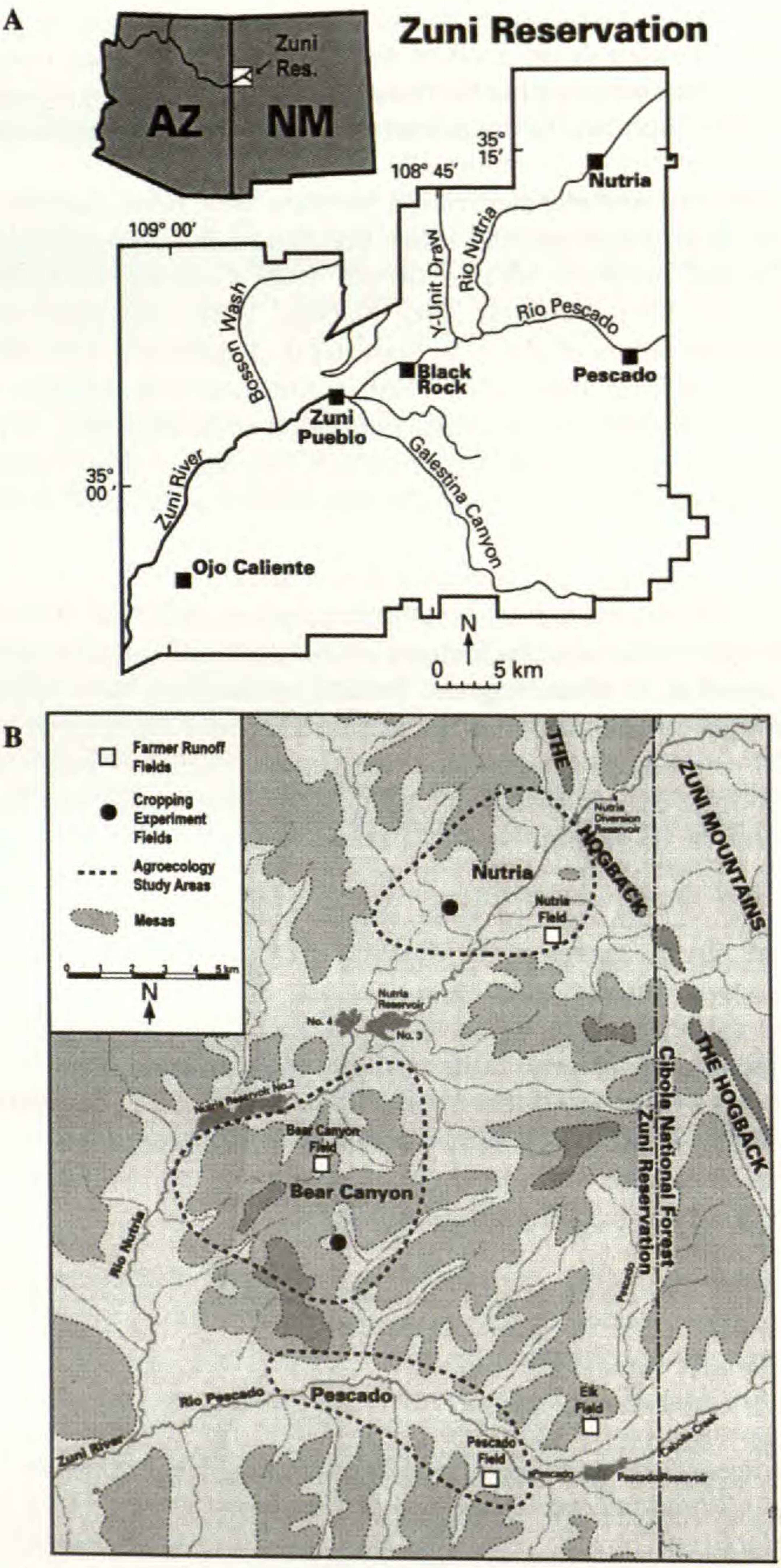

FIGURE 1.—Maps showing the locations of the a) Zuni Reservation, and b) farmer runoff fields included in the study.

From lower to higher areas, soil temperature regime varies from thermic to mesic, and soil moisture regime from aridic to ustic (semiarid). Elevation ranges from 1838 m near the Arizona border to 2347 m on eastern mesas, near the continental divide.

Climate.—Precipitation and temperature at Zuni are largely functions of elevation and landforms, with high spatial and temporal variability. Annual precipitation at Blackrock, in the central part of the reservation at an elevation of 1967 m, averages about 300 mm, but varies widely from year to year (coefficient of variation, 23%) (Balling and Wells 1990; Ferguson and Hart 1985; Kintigh 1985; Tuan et al. 1973). Precipitation generally increases with increasing elevation. Approximately half of the annual precipitation occurs during the summer monsoon season, usually extending from July through September. Summer rains ordinarily occur as highly localized, brief, intense thunderstorms. Traditional runoff agriculture depends on these monsoon rains. The remainder of the precipitation is usually received as lower intensity rain or snow from November through March. May and June are the driest months; June has a long-term average of only 10 mm. Zuni spring and early summer seasons are dry and windy.

The frost-free period, when temperatures exceed 0°C, extends on average from May 16 through October 12, averaging 150 days (s.d. 21 days) at Blackrock (Kintigh 1985; Tuan et al. 1973). The frost-free period is generally shorter at higher elevations. Although temperatures may stay above freezing, spring and early summer night temperatures are often well below the 8 to 10°C minimum required for maize growth (Brandt 1995; Shaw 1988). Local temperature is influenced by wind and terrain, including elevation, aspect, and slope.

The semiarid climate of Zuni supports native vegetation dominated by juniper (*Juniperus* spp.), pinyon (*Pinus edulis*), and Gambel oak (*Quercus gambelii*) woodlands on mesa uplands. Valleys are semiarid grasslands dominated by big sagebrush (*Artemisia tridentata*) and blue grama (*Bouteloua gracilis*).

Zuni Agriculture.—Direct rain alone is insufficient to fully support crop production in most years (Kintigh 1985). Growing season moisture deficit (atmospheric evaporative demand less available soil-stored moisture and precipitation) averages 349 mm (Rhode 1995; Tuan et al. 1973). Zuni farmers report moisture and temperature as their major concerns for crop production (Brandt 1995). Over the centuries, Zuni developed an agricultural system that capitalizes on natural landscape processes to increase water and nutrient availability for crop production and to provide some protection from frost.

Most traditional fields are located where floodwaters occasionally flow. Fields are situated on valley margin alluvial fans and mesa footslopes. These landscape positions permit cold-air drainage away from crops and capture storm floodwaters to augment water availability. Ephemeral storm water, conducted by channel and overland flow from watersheds upslope, is diverted to fields and managed using earthen berms or bunds, stone and/or wooden dams, and shallow ditches (Cushing 1974; Ferguson and Hart 1985; Kintigh 1985). Farmers credit such flows, together with the organic-rich materials transported by runoff water, with supplying moisture and nutrients to support crop production (Norton et al. 1998). Neither synthetic fertilizers nor manure are applied to runoff fields. Crop pro-

ductivity of these fields reflects integrated watershed and crop processes and management.

Although spring winds are particularly drying and can desiccate seedlings, field sites are not specifically selected to provide wind protection. Traditionally, planting was done on the leeward side of the previous year's crop stubble (Cushing 1974:181); the stubble may have provided some wind protection to the emerging seedlings.

Maize (*Zea mays* L.) is the staple crop produced by Zuni farmers using runoff agricultural practices. Local cultivars of open-pollinated maize are sometimes intercropped with beans (*Phaseolus* spp.) and squash (*Cucurbita* spp.), and rotated with fallow periods (Bohrer 1960; Brandt 1995; Manolescu 1994). Maize has long been central to Zuni social, spiritual, and ceremonial life (Cushing 1974; Ferguson and Hart 1985; Kintigh 1985).

Ancient and Historical Contexts.—Zuni agriculture was extensive and well established by 2000 years ago (Damp et al. 2002). Maize radiocarbon dated to about 2200 B.P. has been found at Zuni (Rhode 1990). Prehistoric ceramics associated within field houses indicate that many Zuni runoff fields are at least 1000 years old (Homburg 2000). The archaeological record documents a long-term occupation of the Zuni area, one that is unusually continuous for the Southwest, with increasing reliance on agriculture through time (Damp et al. 2002; Ferguson 1996; Kintigh 1985; Rhode 1990).

Historic records attest to the skill of Zuni as desert agriculturalists. Coronado, who conquered Zuni in A.D. 1540, described Zuni as having great stores of maize (Hammond and Rey 1940). High agricultural productivity at Zuni was also noted in mid-nineteenth century reports of the U.S. military in the region, which depended on the Zuni for maize and other food supplies (Hart 1995). Over 4000 ha were reported in production at Zuni, mostly in rainfed-runoff agriculture, with some fields located nearly 100 km from the Pueblo of Zuni (Ferguson and Hart 1985; Sitgreaves 1853).

Through the early 1900s, most Zuni fields were situated on valley margins to take advantage of storm runoff floodwaters (Brandt 1995; Hart 1995). Zuni also farmed on floodplains around the Pueblo of Zuni and near the farming villages of Nutria, Pescado, and Ojo Caliente, where spring-fed reservoirs and canal and ditch systems facilitated some irrigated crop production (Figure 1). The combination of floodwater and irrigated fields spread risks and improved the likelihood of obtaining sufficient maize yield to supply Zuni current needs and maintain a two-year reserve. Surplus maize was traded with other Native communities, the U.S. military, settlers, and other emigrants during the mid- to late nineteenth century (Hart 1995). By the late 1800s, the traditional territory used by the Zuni had been reduced by 60% to some 2.5 million ha (Cleveland et al. 1995; Hart 1995). At the beginning of the twentieth century, 52% of cultivated land was runoff farmed (Graham 1990; Hart 1995).

Early twentieth-century federal government programs initiated large dam and irrigation projects with the intent of assimilating and transforming Zuni agriculture into the irrigated agriculture norm of the western U.S. (Worster 1985). These programs shifted agriculture from primarily traditional valley margin

fields to the floodplains, which tend to have poorer soils (including highly clayey or sodic soils) and are more prone to frost. Spring-fed irrigated agriculture had been traditionally practiced along the main valleys, but the government-imposed programs radically altered and disrupted traditional Zuni agriculture. Most Zuni moved into the Pueblo of Zuni or Blackrock, leaving few people in the outlying farming villages. Extensive erosion and gully or arroyo downcutting during the late nineteenth and early twentieth centuries further restricted floodwater farming in some areas (Hart 1995). Beginning in the 1930s, many areas that had been runoff farmed became grazing lands in response to federal policies favoring livestock production over farming. By 1935, reservation lands consisted of only 137,700 ha, with just 2100 ha cultivated. Gradually the local economy shifted from reliance on agriculture to wage labor. Although some Zuni continued their customary agricultural practices, most Zuni held non-agricultural jobs, raised livestock, and/or focused their farming efforts on conventional irrigation, producing alfalfa and other forages for cattle and sheep. During the twentieth century, traditional agriculture and knowledge were largely disregarded, and traditional runoff agriculture declined greatly (Cleveland et al. 1995; Hart 1995). By the early 1990s, fewer than 600 ha were cultivated, with just 18% of the cultivated land still runoff farmed (Graham 1990; Hart 1995). Despite disruptions and changes, maize production still plays a vital role in Zuni culture and some traditional runoff maize production persists (Bohrer 1960; Manolescu 1994; Norton et al. 1998; Pawluk 1995).

During the last decade, environmental, cultural, and economic concerns led to the formation of the Zuni Conservation and Sustainable Agriculture Programs, made possible by the Zuni Conservation Act of 1990; the Act resolved the Zuni lawsuit against the U.S. government for land damages resulting partially from forced agricultural and other land use changes (Hart, 1995). These tribal programs were established, in part, to revitalize traditional agricultural practices. As part of that effort, a series of agroecological studies were undertaken to better understand the function and structure of Zuni traditional runoff agriculture (Havener 1999; Homburg 2000; Norton 2000; Sandor et al. 1999). Specific objectives of the study reported here were to:

1. Document contemporary Zuni runoff crop production practices; and
2. Explore the general relationships among management, field characteristics, and maize productivity.

MATERIALS AND METHODS

Fields.—Field characteristics, production practices, and productivity of four runoff fields of Zuni farmers were documented. The study focused on these four fields for several reasons:

- A rapport with the farmer-cooperators had previously been established;
- Fields were actively cultivated in 1998; and
- Fields were located in the farming districts of Pescado and Nutria, prehistorically and historically important farming areas of the reservation (Figure

1). Controlled cropping experiments and other portions of the larger agroecology study were also located in these districts.

Weather Data.—A Campbell Scientific remote weather-precipitation station was installed at one of the controlled cropping experiment fields located in the Bear Canyon unit of the Nutria farming district (Figure 1). Daily minimum and maximum air temperatures and rain events were recorded for May 20 through August 21. Two funnel and collection devices were installed adjacent to each of the two experimental fields to measure rainfall and to sample precipitation for nutrient content.

Soil Information.—Fields were situated on alluvial fans, the traditional setting of runoff fields. Each field was subdivided into three areas based on alluvial fan position: upper, middle, and lower fan. In each fan position of each field, four surface soil samples were collected from the upper 15 cm, approximating the depth of the plow zone; these four samples were combined and a subsample of the composite was analyzed. The Nutria field surface soil sampling, conducted as part of the larger agroecology study, used a different sampling scheme in that samples were collected along two transects in the center of the field (Homburg 2000). Surface samples were analyzed for soil texture, pH, nitrate-nitrogen, plant-available phosphorus, and organic matter content; potassium was not determined because it is usually not limiting in the soils of this region (Sandor and Gersper 1988).

Soil profiles were described and classified according to standard methods (Soil Survey Staff 1993, 1999) in 1 × 1 m or 1 × 2 m pits excavated to a depth of 0.75 to 1.5 m in each field.

Particle size distributions were determined using the sieve and pipette method (Klute 1986: Method 15.4) with samples pretreated with a 30% hydrogen peroxide reagent for digestion of organic matter and a sodium hexametaphosphate solution for clay dispersion.

Chemical analyses were performed by the Iowa State University Soil Testing Laboratory. Air-dried soil samples were sifted through a 2-mm sieve in preparation for analyses. Soil pH was measured electrometrically using a 1:1 suspension (weight basis) of soil and distilled water using a glass electrode (Page et al. 1982: Method 12-2.6). Available phosphorus was measured using the Olsen extraction method (Page et al. 1982: Method 24-5.5.20; extract of 0.5 M $NaHCO_3$ at pH 8). Nitrate-nitrogen was determined colorimetrically (Page et al. 1982: Method 33-8). Percent organic matter was determined by combustion (Page et al. 1982: Method 29-4).

Field Management.—Fields were managed by the farmers in their usual ways to produce their traditional, open-pollinated maize cultivars and other crops. Wilmer Quandelacy and his brothers manage the Elk, Nutria, and Bear Canyon fields. Stanley Sanchez and Carmichael Laiwakete manage the Pescado field.

Information was obtained primarily through in-field visits and discussions with the farmers during the 1998 growing season. Information collected for each field included recent field history; specific crops and cultivars grown, and seed

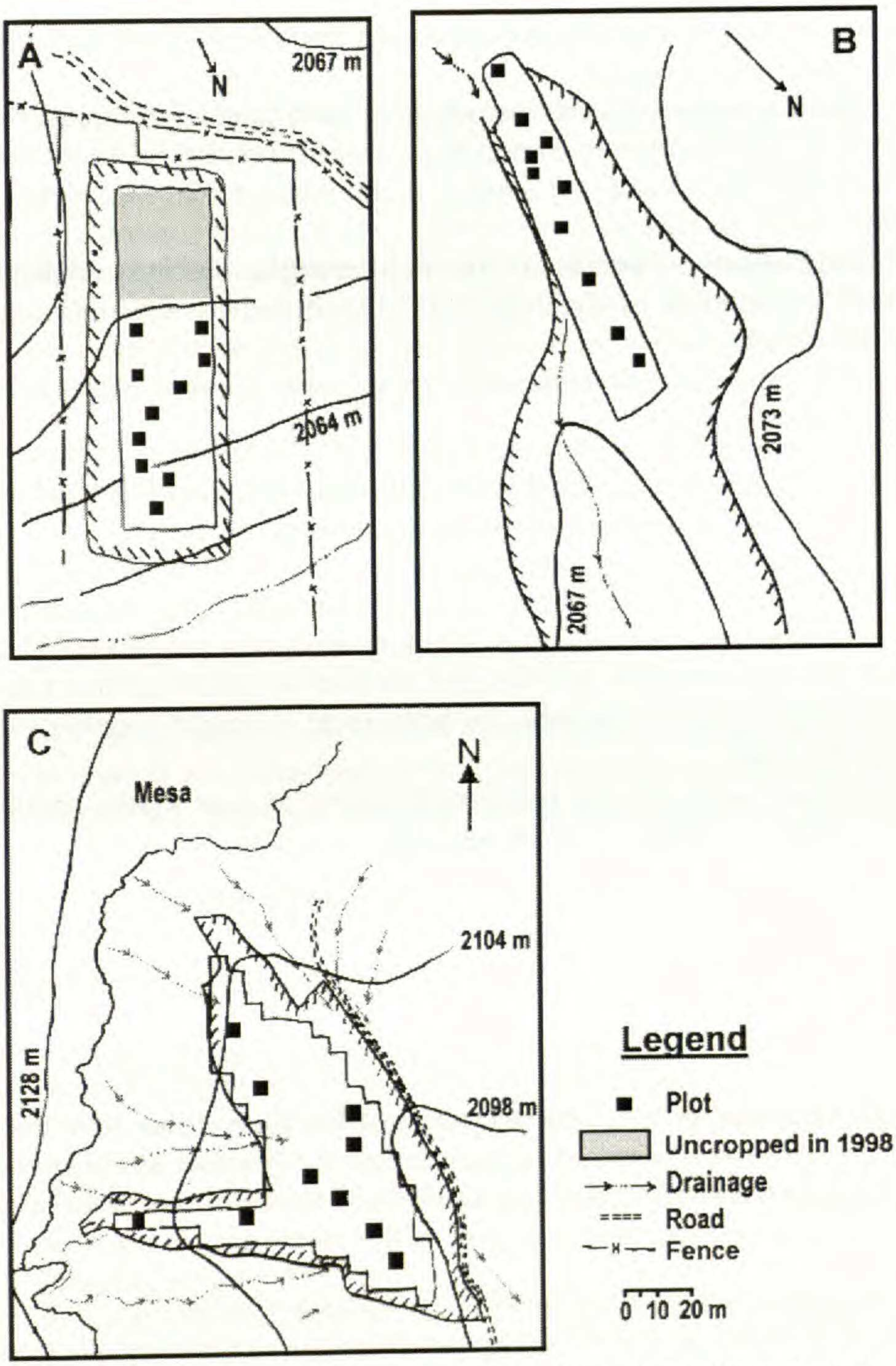

FIGURE 2.—Field maps showing drainages and approximate locations of plots within each field. Each plot is 5 × 5 m. a) Nutria; b) Bear Canyon; and c) Elk fields. Pescado field is not shown. Maps are oriented with upslope shown at the top. (Original maps by Troy Lucio.)

sources; planting date, depth, and method; harvest date; tillage; water and soil management; and weed and pest management practices.

Maize Data.—Each field was mapped and divided into a grid of 5 × 5 m areas ("plots"), with each plot assigned an identifying number. Plots were selected to obtain a representative sampling of each field (Figure 2):

1. Each field was stratified into large sections based on alluvial fan position and other field features;
2. To obtain a representative sampling of each part of the field, two to four numbers were randomly drawn from a pool containing all of the plot numbers within each stratified section of the field, for a total of ten plots per field.
3. Where a selected plot was at the field margin, the next adjacent plot towards the interior of the field was substituted to diminish any edge or border effects.
4. In fields intercropped with other crops, only those plots also containing maize were sampled.

The ten selected plots in each field were outlined with flagging tape or string to facilitate monitoring throughout the growing season.

Maize data were collected from each of the ten plots in each field. These data included stand density, total number of ears, and grain yield of each plot. Maize population density was determined in late July and early August by counting and multiplying the total number of hills and number of plants in five random hills in each plot: Plants/plot = (number of hills/plot) × (mean number of plants in five hills in the plot).

Weed pressure was visually estimated relative to crop plants growing in the field. Weed pressure ratings were defined as:

- "Minimal"—About 25% or less of the plants growing in the field were weeds (i.e., non-crop species);
- "Moderate"—Weeds comprised approximately half of the plants in the field; and
- "Severe"—Weeds were the dominant vegetation in the field.

Harvest occurred on 6, 7, and 9 October 1998. Only those ears deemed sufficiently mature by the farmers were included in the harvest. Harvested ears were counted, dried, hand-shelled, and grain weighed to determine yield. Ears lacking any harvestable grain were not included in the count of number of ears per plot.

Statistical Analysis.—Summary statistics, correlation coefficients, and coefficients of variation (CV) were calculated using the standard functions in Microsoft Excel® 2000. Data are reported as means and standard error (± SE).

RESULTS AND DISCUSSION

Zuni farmers report that maize, beans, squash, and melons are produced for household consumption, to share with community members, to generate seed, to maintain land use rights, and because farming is a time-honored activity (Bohrer 1960; Brandt 1992; Manolescu 1994). Crop production, however, is not the primary economic activity of most Zuni farmers today, including the farmer-cooperators in this study (Brandt 1992; Cleveland et al. 1995; Manolescu 1994). Farmers note that fields are often left unplanted due to the lack of time, water, equipment, or other production constraints. Although these constraints also often limit their

farming activities, the farmers in this study plant maize in one or more fields every year.

One farmer and his family have fields in both the Pescado and Nutria farming districts, whereas the other farmer-cooperators have several fields in different landscape settings in the Pescado district. Most Zuni farmers have two or more fields, often in different parts of the reservation (Manolescu 1994). The use of scattered multiple fields traditionally served to buffer the agricultural system against crop failure (Cleveland et al. 1995; Ferguson and Hart 1985). Overall yield stability results from differences in growing season conditions (moisture and temperature), soils, and pests among diverse field locations.

Field Characteristics.—Farmers in this study report that field selection is based on several criteria:

- land use rights;
- probability of the field receiving sufficient water to support crop production; and
- field size and qualities, including soil texture and natural vegetation.

In addition, one farmer specifically avoids areas with sparse or weedy vegetation. These location criteria are consistent with those reported by others (Cleveland et al. 1995; Cushing 1974; Ferguson and Hart 1985; Kintigh 1985; Manolescu 1994; Norton 2000; Pawluk 1995; Prevost et al. 1993).

The four fields studied are situated to receive storm floodwaters from upslope. One of the two fields in each farming district studied was situated in an upper alluvial fan and the other field was located more distally on a fan.

Mean elevation of these four fields is 2079 m. Known fields in the Pescado and Nutria areas are concentrated between 2000 and 2150 m elevation. Zuni and Navajo have farmed a few sites in the area at elevations up to 2250 m (Ferguson 1985; Rhode 1990). In an archaeological survey of Zuni agricultural sites, Rhode (1990) found that the majority of sites occur between 2010 and 2075 m, with an overall range of 1950 to 2250 m. Cold temperatures ordinarily make the growing season length too short for maize production at elevations much above 2200 m in this region (Brandt 1995; Sandor 1995).

Historically, the cropped area of these fields was substantially greater than the area cultivated in 1998 (Table 1). The cultivated area of these fields averaged 0.69 ha ($\pm$ 0.37); the three fields managed by one family averaged 0.32 ha. Most Zuni fields today are an estimated 4 ha or less (Manolescu 1994). Farmers indicate that time constraints limit the area that they can manage. In addition, they note that periodically leaving fields or sections of fields uncropped for several years is important to maintain field productivity. Generally, fields or parts of fields are cropped for two or three years and then left fallow for one to four or more years. Across the reservation, we observed that fields cropped for more than several consecutive years tended to exhibit nutrient deficiencies. The effectiveness of fallowing to accumulate nutrients or disrupt pest cycles depends on the length of the fallow period and the field's vegetation during the fallow period.

Bear Canyon field was in its second consecutive year of cropping; the farmer estimated that it had been fallow for the previous 10 to 12 years. The Nutria field

TABLE 1.—Field locations and physical environments.

Field name	Farming district	Landform	Watershed size (ha)	Field elevation (m)	Field size (ha)	1998 Cultivated area (ha)	Slope (%)
Bear Canyon	Lower Nutria (Bear Canyon Unit)	upper alluvial fan	39	2067	2.9	0.3	3
Nutria	Lower Nutria	lower fan	52	2070	13.8	0.3	5
Elk	Pescado	upper fan	28	2100	0.4	0.4	3
Pescado	Pescado	middle fan	120[1]	2080	2 to 7[2]	1.8	3

[1] Data from Norton (1996:62).
[2] Data from Graham (1990:99). Historically, the cropped area of this field has ranged between 2 and 7 ha.

had been cropped for about five consecutive years. Crop production at the Pescado field rotates every couple of years between two large sections; the section cropped in 1998 was in its second successive year of production. To the farmers' knowledge, Elk field had not been cropped before they cleared the site of sagebrush and pinyon for the 1997 growing season. This new field was developed because the farmer wanted to try a new site and this one satisfied his criteria: the family had land use rights to the site; he had observed that water flowed onto the site from two directions; it had sandy surface soil and vigorous, but not weedy, vegetation; and it was accessible by truck. With the exception of Elk field, historical and archaeological evidence indicate that the other three fields have been cropped occasionally since at least A.D. 1000 (Homburg 2000).

Soil classification and physical properties. Soils in most of the fields are classified as Alfisols, and all four fields have loamy to sandy surface textures (Table 2). Among his selection criteria, one farmer evaluates potential field sites based on soil texture, favoring those with sandy surface soils. Medium to moderately coarse surface soil textures, such as sandy loam and loams, are well suited for crop production because of their favorable water infiltration and water-holding properties, aeration, and plant-available nutrients (Brady and Weil 2002). Surface soil particle size sorting was evident in each field, generally resulting in coarser textures in the upper field areas with clay and silt increasing and sand decreasing downslope (Table 2). Fields situated more distally on alluvial fans exhibited nearly twice the clay content in the upper 15 cm than did fields located on upper alluvial fans, averaging 24% and 13% clay, respectively. The trend of coarser to finer particle sizes from upper to lower parts of alluvial fans agrees with observations from other studies at Zuni (Homburg 2000; Norton 1996; Pawluk 1995) and with general knowledge of alluvial fan geomorphology (e.g., Waters 1992).

Stratification in the soil profile of each field demonstrates recurring depositional events interspersed with soil horizons marking periods of geomorphic stability (Homburg 2000). Soil development is indicated by the accumulation of illuvial clay, forming argillic horizons. Elk field is a good example of a field having younger, coarser alluvial fan sediment overlying stratified alluvium and a buried argillic horizon. Compared to its overlying topsoils, plant available moisture was 57% greater on a relative basis, and 7% greater on an absolute basis in argillic

TABLE 2.—Surface soil (0–15 cm) physical properties and soil taxonomic classification of fields.

Field name	Relative field position of surface sample	Sand content (%)	Silt content (%)	Clay content (%)	Textural class	Soil classification (Family)
Bear Canyon	upper	72.5	18.0	9.5	sand loam	Fine-loamy, mixed, mesic, Aridic Haplustalf[2]
	mid-field	69.9	18.9	11.2	sandy loam	
	lower	51.8	32.0	16.1	loam	
	Mean	64.7	23.0	12.3		
Nutria[1]	upper mid-field	49	30	21	loam	Fine-loamy, mixed, mesic, Aridic Haplustalf
	upper mid-field	21	49	30	clay loam	
	mid-field	41	36	23	loam	
	mid-field	16	52	32	silty clay loam	
	Mean	32	42	26		
Elk	upper	74.3	15.3	10.4	sandy loam	Coarse-loamy, mixed, nonacid, mesic, Aridic Ustifluvent with buried argillic horizon
	mid-field	66.1	17.2	16.7	sandy loam	
	lower	61.3	25.9	12.8	sandy loam	
	Mean	67.2	19.5	13.3		
Pescado	upper mid-field	55.6	26.6	17.8	sandy loam	Fine-loamy, mixed, mesic, Aridic Haplustalf. Minimally developed argillic horizon
	mid-field	45.7	34.5	19.8	loam	
	lower	28.6	45.0	26.4	loam	
	Mean	43.3	35.4	21.3		

[1] Data from Homburg (2000:240).
[2] Soil profile excavated about 100 m downslope on same alluvial fan as cultivated field.

horizons in the Pescado field (Homburg 2000:98). Fields having soil profiles with coarser textured surface layers underlain by argillic horizons would favor crop production in runoff systems. The stratification and argillic horizon help retain moisture within the crop rooting zone. The coarser surface promotes rapid water infiltration, and the underlying more clayey zone holds water in the root zone, reducing percolation losses (Homburg 2000; Sandor 1995). In addition, a coarser surface reduces evaporative losses due to the larger pore size and concomitant reduced upward capillary movement of water.

Zuni clearly recognize the relationship between soil moisture and soil texture (Norton 2000; Pawluk 1995). Cushing (1974:181), writing in the 1880s, noted that ". . . the little drifts of sandy soil protect the underlying loam in which the kernels are embedded. . . ." Other Native Americans in the region similarly select runoff fields with coarser surface layers underlain by more clayey zones, including the Tohono O'odham (Nabhan 1984) and Hopi (Bradfield 1971; Hack 1942; Prevost et al. 1984).

Soil chemical properties. Farmers in this study do not apply synthetic fertil-

TABLE 3.—Surface soil (0–15 cm) chemical properties by relative field position.

Field name	Relative field location of surface sample	pH	Available P (mg/kg)	Nitrate-N (mg/kg)	Organic matter content (%)
Bear Canyon	upper	7.0	2	12	1.8
	mid-field	6.9	4	21	1.9
	lower	7.0	<1*	7	2.8
	Mean	7.0	2	13	2.2
Nutria	upper mid-field	8.0	8	19	2.5
	upper mid-field	7.8	6	34	3.8
	mid-field	7.9	7	13	2.7
	mid-field	7.8	6	18	4.5
	Mean	7.9	6	21	3.4
Elk	upper	7.0	6	13	1.2
	mid-field	7.1	2	8	0.9
	lower	6.6	1	23	1.7
	Mean	6.9	3	14	1.2
Pescado	upper mid-field	7.6	6	10	1.7
	mid-field	7.5	6	17	2.1
	lower	7.1	8	26	3.5
	Mean	7.4	6	18	2.4

* Available P in this sample was below detectable level and treated as zero in calculation of field mean.

izers or manure to their fields; throughout the Southwest, fertilizer amendments are generally not used in traditional systems (Sandor 1995). Because horses are pastured in the Pescado field following harvest and cattle are sometimes grazed in the Nutria field, these fields receive some minimal manure input; other fields may be occasionally grazed by sheep. These farmers, however, attribute the fertility of their fields to storm runoff and materials it deposits on the fields, and to periodic fallowing. The contribution of runoff to soil fertility has been recognized by generations of Zuni (Cushing 1974; Manolescu 1994; Pawluk 1995). Cushing (1974) described Zuni management of storm runoff for the express purposes of not only irrigating the crop, but enriching the soil as well. This important relationship between landscape processes and soil qualities is also embedded in Zuni soil terms; for example, the Zuni word for the materials transported by runoff translates to "tree soil," recognizing the upslope source of the organic debris (Pawluk 1995).

Soil and nutrient analyses showed that the four fields have optimum to somewhat alkaline pH for maize growth and adequate macronutrients for these low crop density systems. Average soil pH in the upper 15 cm of the four fields is 7.3 (± 0.2) (Table 3). Twelve Zuni field areas surveyed by Manolescu (1994) exhibited somewhat higher pH, ranging from 7.2 to 7.7, and averaging 7.5. Optimum pH for maize is between 5.5 and 7.0 (Olson and Sander 1988).

Nitrate-nitrogen, a plant-available form of N, of the four fields averaged 16.5 mg/kg (± 1.8), and available P averaged 4.3 mg/kg (± 1.0) (Table 3). Nitrate-nitrogen in each of these fields was considerably greater than, and available P

was similar to, that reported for 12 other Zuni farmer fields, which averaged 4.9 mg/kg nitrate-nitrogen and 5.9 mg/kg available P (Manolescu 1994). Soils of the controlled experiment fields of the larger agroecology study had 8.5 mg/kg available P (Homburg 2000); nitrogen mineralization studies of these soils showed average nitrate-nitrogen of 2.6 (± 0.4) to 22.2 (±1.4) mg/kg at 0 and 70 days incubation, respectively, and average ammonium, another plant-available form of N, ranged from 2.3 (± 0.1) to 0.5 (± 0.0) mg/kg at 0 and 70 days incubation, respectively (Carl S. White, unpublished data[1]). Available N varies during the season with moisture, temperature, and microbial activity (Brady and Weil 2002). Although maize in this system is planted deeply, it is likely that roots are present in this upper soil layer. Maize adventitious roots, arising from basal nodes of the stem, are commonly located near the soil surface regardless of seeding depth; adventitious roots were observed in Zuni maize. These roots extract nutrients and water from upper soil layers.

Specific crop nutrient requirements in many soils in the Southwest are not well understood. The amounts of nitrate-nitrogen and available P at each field are interpreted as moderate and low, respectively, based on the nutrient requirements established for conventional commercial agricultural production in New Mexico; conventional systems, however, require relatively higher amounts of nutrients to support higher plant population densities and high yields. Nitrate-nitrogen amounts between 10 and 30 mg/kg are considered moderate (Cihacek et al. 1992). Available P levels below 8 mg/kg are rated as very low. In Arizona soils, however, available P levels greater than 5 mg/kg are considered sufficient (Doerge 1985). The lack of nutrient deficiency symptoms in the farmers' fields, with the exception of the Pescado field, suggests that nutrient levels were adequate to support these low-density crops (9650 plants/ha). Maize plants in the Pescado field were stunted and displayed symptoms of P deficiency, likely resulting from severe weed competition for both nutrients and water. When water becomes limiting, nutrient uptake can become restricted.

Agricultural soils in semiarid environments are commonly deficient in N (Ludwig 1987; Nabhan 1984; Sandor and Gersper 1988; West 1991). In this runoff agricultural system, however, storm flows transport organic matter, sediments, and nutrients to fields. As water flows over the landscape, nutrients are dissolved and transported. Analyses of runoff water collected at the controlled experiment fields indicate that these waters deliver N and other nutrients from the watershed to the field (Norton 2000). In addition, precipitation itself contributes plant usable forms of N (nitrate-nitrogen and ammonium) to the system (White and Thomas 1999).

Soil organisms and watershed vegetation also likely contribute to the nutrient status of the fields (Havener et al. 1999). Soil microbial biomass did not differ significantly between cultivated and uncultivated soils at Zuni, contrary to the trend of decreased microorganisms in conventional production fields in the U.S. Corn Belt (Havener 1999). Field-grown Zuni maize roots exhibit substantial amounts of mycorrhiza formation. Nutrient uptake of some unimproved maize cultivars can be enhanced by mycorrhizae (Khalil et al. 1994); the effect of mycorrhizal infection on Zuni maize has not been tested. Vegetation mapping of watersheds above fields in the Pescado and Nutria districts, including the Pescado

field watershed, revealed the common occurrence of symbiotic nitrogen-fixing plants: lupine (*Lupinus* spp.), scurfpea (*Psoralea tunuflora*), deer vetch (*Lotus wrightii*), and mountain mahogany (*Cercocarpus montanus*), actinomycete nodulated vascular plants, and cryptogamic crusts (Havener 1999; Homburg 2000; Norton 1996). Symbiotic soil bacteria that associate with legumes convert atmospheric N into a form usable by plants. Cryptogamic crusts are a symbiotic associations of fungi and algae that also fix N. Cryptogamic crusts are important sources of N in semiarid ecosystems (Metting 1991). In addition to nutrients dissolved in runoff water, the organic debris deposited on fields by storm flows provides nutrients as the debris decomposes (Norton 2000).

Organic matter averaged 2.3% (± 0.5) by mass. Typically, soils developed in semiarid zones are low in organic matter, near 0 to about 3 or 4% (Klemmedson 1989). Organic matter contributes to soil water-holding capacity and nutrient availability for crop production (Brady and Weil 2002).

Based on his fieldwork in the early 1880s, Cushing (1974:164–166, 181) noted the importance of runoff to renew soil fertility and the use of an in-field fallowing system in which the new crop was planted about 10 to 12 cm east of the previous years' row of crop stubble to avoid successively planting in the same place. The stubble also served as a windbreak, causing wind-blown sediment to be deposited on the leeward side of the stubble. Wind barriers of brush were erected on the western edges of fields to promote accumulation of eolian sediment. These windbreaks may also have reduced seedling desiccation by the dry spring winds. Zuni have long understood the dynamics of landscape processes relative to crop production.

Precipitation and Runoff.—Summer rains in the Pescado and Nutria districts in 1998 occurred in a typical pattern, beginning in early July. Rain events were noted, but amounts were not recorded at the farmers' fields. Mid-May through mid-September 1998, 170 mm and 175 mm rain was received at the controlled experiment fields located in the Bear Canyon and Nutria areas, respectively, about 10 to 12% above average; mean precipitation for this period near Blackrock is 155 mm (Kintigh 1985). These rain amounts, however, are near the lower limit for maize production.

Maize is generally produced in areas receiving at least 250 mm precipitation annually, or 150 mm during the growing season (Shaw 1988). To produce high yields, maize requires an estimated total of 500 to 800 mm water during the growing season (Critchley and Siegert 1991). Daily consumptive water use can average more than 6 mm in semiarid to arid climates (Rhoads and Yonts 1984); at Clovis, New Mexico, maize potential daily water use rates range from 7.5 to 9.8 mm/day (Abdul-Jabbar et al. 1983). The actual amount of growing season rain needed for productivity, however, varies with the specific maize cultivar, root length density, plant population density, growing season length, stored soil moisture, rain temporal distribution relative to crop developmental stages, atmospheric water demand (which depends on solar radiation, temperature, wind, and humidity), and irrigation or other water supplements. Greater yields are generally obtained with greater moisture availability (Rhoads and Bennett 1990). The mois-

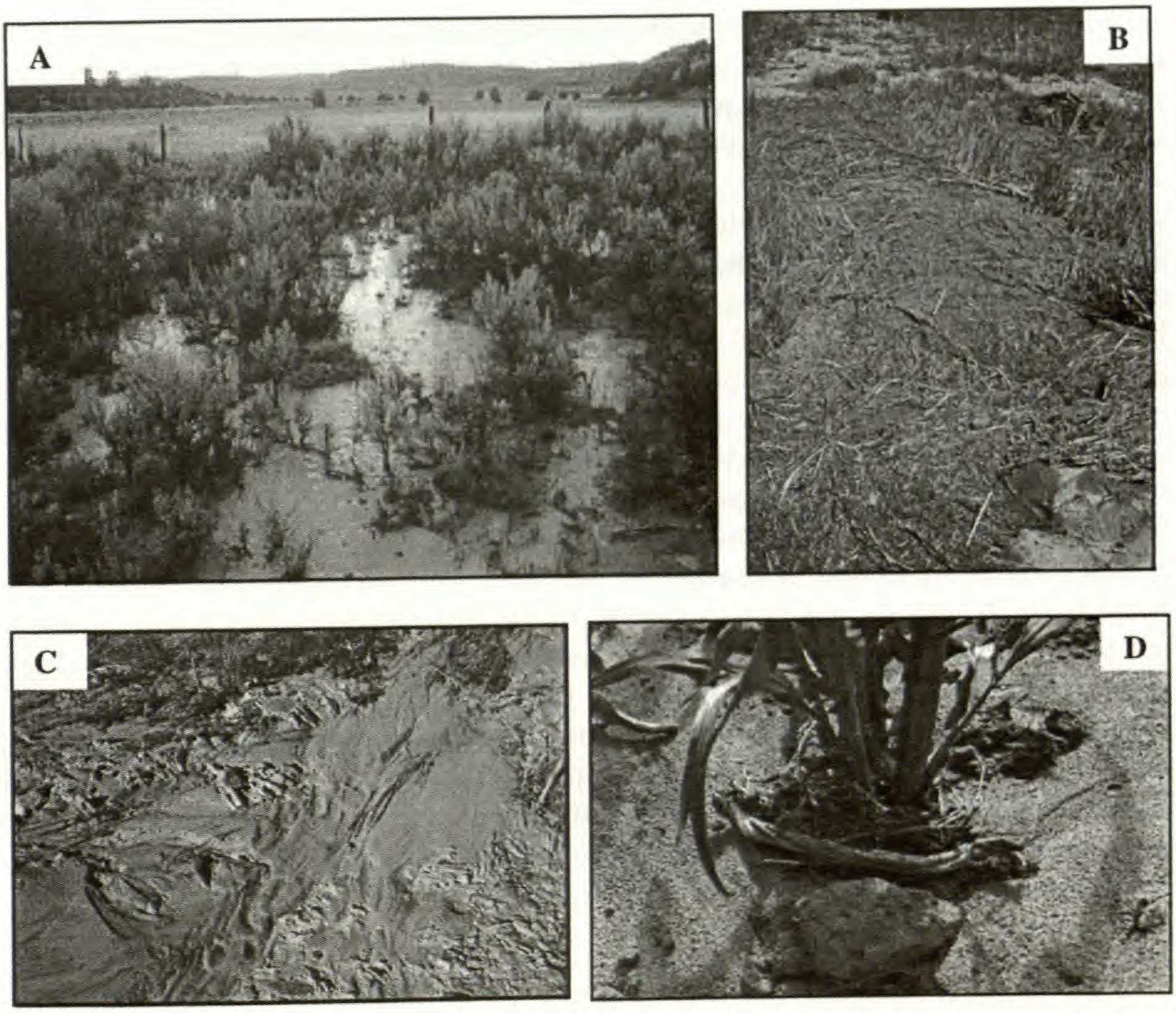

FIGURE 3.—Runoff components: a) runoff water; b) debris and sediments washed into field with storm runoff; c) sediments deposited on field; and d) debris caught by maize hill.

ture requirement or responsiveness of Zuni maize has not been specifically examined.

Rain was sufficient to generate two runoff events at the Pescado and Nutria fields, three at the Elk field, and two or three at the Bear Canyon field (after some storms, muddy roads prevented field access to check for runoff). After each runoff event, an assortment of debris was observed on the field. Storm runoff water washes sediments and organic materials in various stages of decomposition into fields from upslope; such materials often accumulate around the bases of maize hills (Figure 3). The frequency of summer runoff events observed in 1998 corroborate farmers' perceptions of the usual number of such events on their respective fields: one or more at Pescado, and two to three events at the other fields.

Runoff amount and frequency is a function of the area of the watershed, the amount and intensity of the rainstorm, slope, soil permeability, type and density of vegetative cover, surface litter or stones, and antecedent soil moisture (Shreve 1934). In arid regions, smaller watersheds have a greater frequency of runoff events and greater runoff yield per unit area (Osborn and Renard 1970). The number of runoff events observed in 1998 in these fields is consistent with the

general inverse relationship between watershed area and runoff frequency in arid environments. Elk and Bear Canyon fields have smaller watersheds than the Nutria and Pescado fields and would be expected to have more frequent runoff events with greater water yield (Table 1). The effective size of the Nutria field watershed, however, is reduced by a road perpendicular to the slope, about 100 m above the field; the road interrupts storm flows from upslope, channeling runoff away from the field. Elk field is situated at the confluence of multiple ephemeral waterways near the base of a mesa, increasing its opportunity for runoff. Runoff events at Bear Canyon had sufficient volume and velocity to cause some plant washouts and soil erosion; damaged plants were propped up by "hilling" to improve plant standability against wind and flood. Zuni farmers, like other Native American farmers, traditionally hilled or pushed soil up around the base of maize plants as they hoed weeds, adding structural strength to the plant cluster (e.g., Biggar 1918; Castetter and Bell 1942:175; Cushing 1974:203; Will and Hyde 1917:83; Wilson 1987:26). Although hilling was observed in some Zuni fields, the farmers in this study did not routinely hill because of time constraints. To slow water velocity and reduce the risks of washouts and erosion, the farmer later installed earthen berms and brush and rock barriers in the Bear Canyon field. The other three fields in this study had no current water or erosion control structures. Control structures were observed in other cultivated and uncultivated Zuni fields. Traditionally, runoff was actively managed with control structures to keep large debris off the field, to slow water to promote infiltration, and to reduce erosion and plant washouts (Brandt 1995; Cushing 1974; Ferguson and Hart 1985; Kintigh 1985; Norton and Laahty 1999).

Direct rain, together with storm floodwaters, apparently provided adequate water to support the crop in the Elk and Bear Canyon fields; maize plants in these fields exhibited mild wilting for only brief intervals. Nutria and Pescado fields showed water-deficit stress symptoms more often and for longer durations, apparently because of less water and greater interplant and/or weed competition; the Nutria field had a relatively high plant population density, and both fields had greater weed pressure than the other fields.

Production Practices.—Crop management today is commonly determined by availability of time, equipment, and transportation to the fields (Brandt 1992; Manolescu 1994). Each of the fields is at least 30 km from the Pueblo of Zuni, where the farmers reside. Maize production is important to these farmers, but it is not their main economic activity. As a result, production practices varied somewhat among farmers and fields, with some fields receiving more attention than others. One of the main objectives of cropping the Pescado field was to retain use rights and for pasturing horses after the maize harvest; management of this field was limited to field preparation, planting, and harvesting. The stated reasons for cropping the other fields were to obtain sufficient maize to satisfy the family's needs, produce seed for the next season and to share with other community members, and because farming is enjoyable.

Maize cultivars. Farmers in this study usually produce at least two Zuni folk varieties of open-pollinated maize; these cultivars have a mix of flinty and floury endosperms. Farmers define maize type based on kernel color. Both white and

blue maize were produced in each of the four fields; these are the most common types grown at Zuni (Bohrer 1960; Brandt 1992; Manolescu 1994). Zuni red maize and sweet corn were also planted in the Pescado field.

Farmers report that the type and amount of maize they plant depends on need. Grain is used for direct human consumption, ceremony, and seed; vegetative parts are used for livestock fodder. Like most Zuni farmers, these farmers save their own seed from year to year, occasionally obtaining seed from other community members. Some Zuni farmers also obtain seed from other Native American communities in the area, including Hopi and Acoma. Nearly 75% of 50 Zuni households surveyed grow Zuni folk varieties of maize (Brandt 1992); these cultivars are believed to perform better than commercial varieties or those obtained from the Rio Grande pueblos in central New Mexico.

Different maize types were sown in different parts of each of the fields monitored. Sweet corn was planted in the center of the Pescado field to "hide" it from the elk and other herbivores. Planting the maize types separately in a field is a matter of convenience (Figure 4). Farmers do not consider cross-pollination among maize types a problem because the types "do not mix;" we observed that these types tend to flower at different times, which reduces the probability of cross-pollination among cultivars.

Planting practices. Fields were planted between 13 May and 1 June 1998. These farmers prefer to plant earlier, as early as temperatures permit, and consider early June to be the latest for planting maize. Other farmers also report that planting occurs as early as mid-April and should be complete before June (Manolescu 1994). During the late nineteenth century, Zuni commonly planted in May (Cushing 1974:174). Temperature and water-deficits are the main production constraints at Zuni and throughout the southwestern U.S. Planting as early as temperatures permit increases the likelihood of sufficient moisture availability for germination and emergence, and attainment of crop maturity before fall frost.

Cold temperatures delimit the growing season at Zuni. In the eastern part of the reservation, the growing season ordinarily extends from late April or early May through late September or early October. The temperature range for normal maize growth is approximately 8 or 10 to 40°C, with optimum growth occurring at about 30°C, assuming water is not limiting (Shaw 1988). Maize usually survives at ambient temperatures between −4 and 50°C, although injury will occur at either temperature extreme. Although temperatures may remain above freezing, spring temperatures at Zuni are often cool and early summer frosts are not uncommon at these elevations (about 2000 to 2150 m). Frost occurred in the Nutria farming district as late as July 1 in 1997 and June 19 in 1998, causing some tissue damage but not plant death.

Mean daily air temperature for the 1998 growing season at the controlled experiment field located in the Bear Canyon area was relatively cool, 16.8°C; season mean daily maximum and minimum temperatures were 27.3 and 6.4°C, respectively. May through September mean temperature at Blackrock is 18.6°C (Kintigh 1985). Maize generally requires a summer average minimum temperature greater than 13°C (Shaw 1988). Because of frequent exposure to cool temperatures over generations, Zuni maize has likely evolved mechanisms that confer cold tolerance; cold tolerance of these cultivars has not been documented.

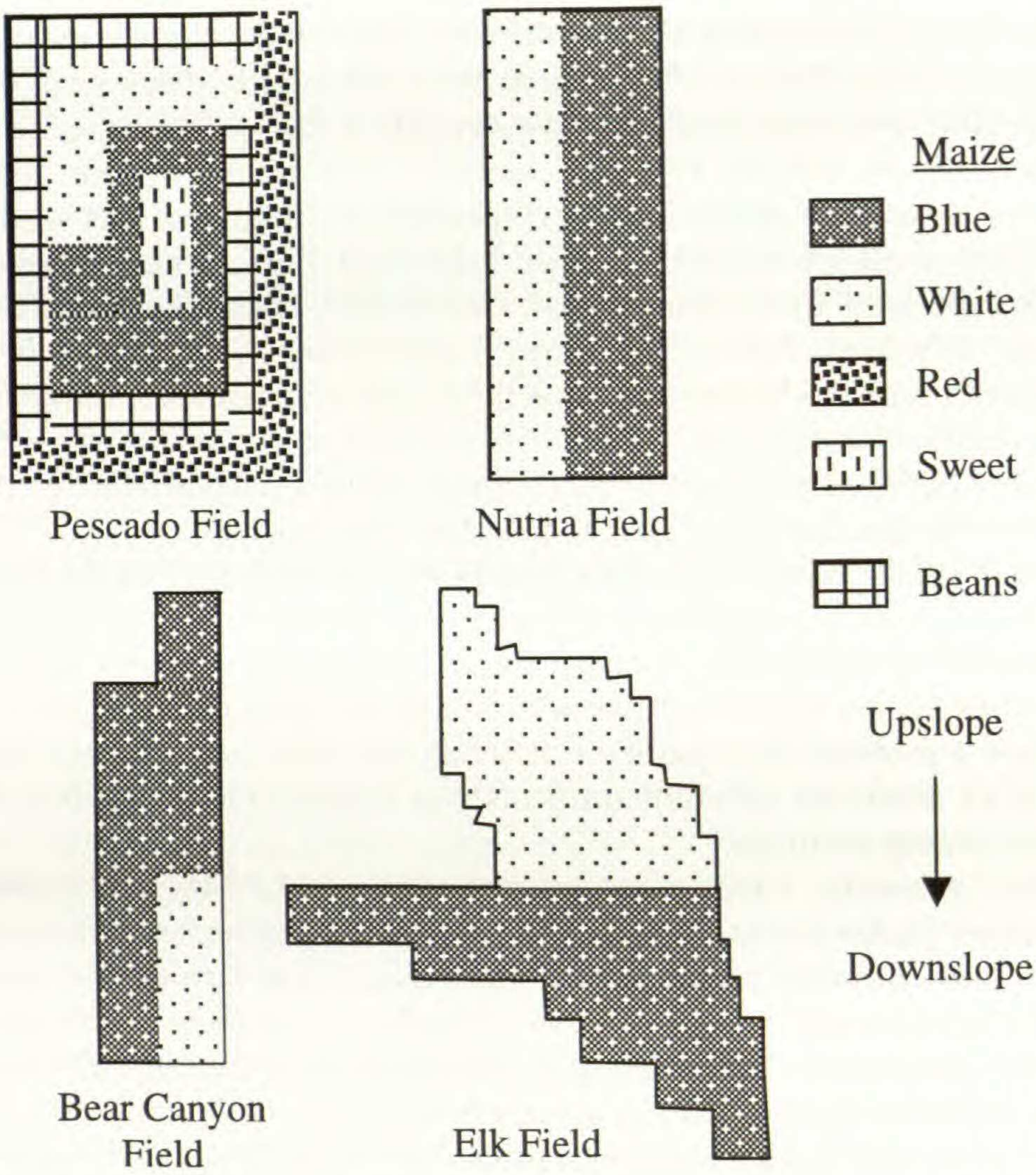

FIGURE 4.—Schematics of the planting patterns by maize cultivar type in the Nutria, Pescado, Bear Canyon, and Elk fields, 1998. Pinto bean, watermelon, and pumpkin were interspersed randomly in the Bear Canyon field; pinto bean was planted in one of the "circles" of the Pescado field. Not to scale.

Temperature has a direct effect on the rate of development, with cooler temperatures slowing and warmer temperatures hastening growth and development. Depending on temperature fluctuations, the number of days needed to attain maturity can vary widely from year to year. The cultivars produced in this study required about 125 days to attain maturity. Although Zuni blue maize produced in the experimental fields has a reputed maturity range of 95 to 120 days, nearly 130 days from planting was required to reach maturity in 1998 (Muenchrath, unpublished data). Cool soil temperatures at planting may have hindered germination and emergence, and the relatively cool air temperatures likely slowed developmental processes and delayed maturity. Hopi maize, adapted to northeastern Arizona and commonly traded with Zuni, matures in 115 to 130 days (Bradfield 1971).

All four fields were prepared for planting by plowing. The Pescado field was disked after plowing, creating a rough seedbed with many large clods. While disking, the driver planted seed by dropping two to three kernels at a time from

TABLE 4.—Production practices as reported by farmers or measured. Bear Canyon, Nutria, and Elk fields are managed by a single extended family; Pescado field is managed by two other farmers.

Field name	Planting date 1998	Zuni maize (seed color or type)	Planting depth (cm)	Seeds planted per hill (number)	Hill spacing, approx. equidistant Stated (m)	Actual[2] (m)
Bear Canyon	June 1	blue and white	15	4	1.5 to 2.5[1]	1.3
Nutria	May 15	blue and white	15	4	1.5 to 2.5[1]	0.6
Elk	May 13	blue and white	15–20	4	1.5 to 2.5[1]	1.1
Pescado	May 25	blue, white, red, and sweet	15–30	2–3	Unsure	3.7

[1] Farmers reported hill spacing as "3 to 4 steps," a distance estimated to be equivalent to about 1.5 to 2.5 m.
[2] Actual hill spacing calculated from mean hill density per plot.

his hand, beginning in the middle of the field and proceeding in concentric passes. Seed type was changed wherever the seed supply of one type ran out (Figure 4). The Bear Canyon and Elk fields were also planted by the tractor driver dropping about four seeds together into the furrow opened during the previous pass of the plow and adjacent to the tractor. In the Nutria field, people walking behind the tractor hand planted maize, usually placing four kernels together into the side or bottom of the furrow, wherever the soil seemed "softer." Seed is covered as the next furrow is plowed. Nutria and Elk fields were harrowed the day after plowing and planting to break up soil clods, to better cover seed, and to smooth the field surface; the farmer was unable to get to the Bear Canyon field to harrow it. Other Zuni farmers use similar field preparation and planting practices, sowing two to five seeds per cluster (Manolescu 1994).

Traditionally maize was sown by hand using a digging or planting stick to open a hole in the soil for seed placement (Cushing 1974:175). Farmers recognize that this traditional 'no-till' approach conserves soil moisture by limiting the soil volume opened and exposed to the dry, windy conditions (Ford 1985). Soil moisture accumulated during the winter is relied on for germination and seedling establishment. Zuni springs are usually dry and windy, reducing moisture availability as the season progresses until the summer rains arrive, usually in July. Cushing (1974:181) wrote that the ". . . country of the Zunis is so dry that the seeds have to be planted to great depths—even at the expense of great delay in their growth," usually at about 10 to 18 cm; 12 to 20 kernels were planted in each hole, in part, because it was expected that some would not emerge successfully. Collins (1914:299) notes that ". . . there is no fixed depth for planting, the custom being to plant deep enough to place the seed in moist soil," commonly at depths of 15 to 45 cm. Although the desired planting depth is still based on the location of moist soil, actual planting depth is now largely determined by plowing depth; fields were plowed to depths of 15 to 40 cm and seed planted at 15 to 30 cm in this study (Table 4). Manolescu (1994) reports that 8 to 20 cm is the common planting depth used at Zuni today.

Seeds will not germinate in dry soil. Thus, farmers are reluctant to risk seed

TABLE 5.—Mean plants per hill, hills per plot, and estimated plants per plot and resulting plant population density. Standard error indicates the variability among plots within field.

Field name	Plants per hill Mean	Plants per hill ± SE	Hills per plot Mean	Hills per plot ± SE	Estimated[1] plants per plot Mean	Estimated[1] plants per plot ± SE	Estimated[2] population density (plants/ha) Mean	Estimated[2] population density (plants/ha) ± SE
Bear Canyon	1.9	0.2	10.5	0.7	20.7	3.1	8,288	1,229
Nutria	2.4	0.2	18.4	2.9	45.6	8.2	18,248	3,298
Elk	2.0	0.2	11.1	0.9	23.5	3.6	9,384	1,422
Pescado	1.1	0.1	6.1	1.1	6.7	1.1	2,680	448
Across Fields:	1.9	0.1	11.5	1.1	24.1	3.2	9,650	1,281

[1] Calculated with the formula: Estimated plants/plot = [(mean number of plants in 5 random hills/plot)(hills/plot)].
[2] Calculated from the mean of 10 plots in each field: Estimated field population density = [(mean estimated number of plants/plot)(25 m^2/plot)(10,000 m^2/ha)].

if conditions are dry. Planting decisions are often dependent on spring soil moisture; some Zuni farmers assess soil moisture conditions in March by digging a test hole in the field (Carol Brandt, personal communication 2001[2]). When soil conditions are dry in the plow zone, the farmers in our study sometimes soak seed overnight to two days in spring water to hasten germination. Seed were soaked before planting at the Elk and Nutria fields in 1998. Soaking seed before planting, however, did not provide a significant increase in plant population density relative to fields planted with dry kernels (Table 5). Although not mentioned by the farmers in this study, other farmers indicate that seed is soaked to speed germination when planting is relatively late (Manolescu 1994). Neither Cushing (1974) nor Collins (1914) report that Zuni traditionally soaked seed before planting.

In addition to moisture availability, deep planting (greater than the 5 cm commonly used in commercial maize production systems) may provide other benefits to the crop. Deep planting can extend the growing season in the spring. Because the sensitive growing point, or meristematic region, where cells are actively dividing, remains underground longer when planted deeply, the plant is better protected from late spring frosts. Above-ground tissues may be frost damaged, but the plant will survive and recover as long as the growing point is not killed. Deep planting also likely reduces bird predation of seedlings, and better anchors plants against wind and washout by storm runoff.

Farmers space clumped maize plantings or "hills" roughly equidistantly, about "three to four paces" apart, consistent with the traditional spacing used in the late nineteenth century (Cushing 1974); this distance is estimated to be equivalent to about 1.5 to 2.5 m. Actual row spacing in farmers' fields averaged 1.7 m (± 0.7) (Table 4). Row spacing in nine other Zuni fields ranged from 0.8 to 2.2 m and averaged 1.4 m (Manolescu 1994).

Bean (*Phaseolus vulgaris*), watermelon (*Citrullus vulgaris*), and squash (*Cucurbita maxima*) seeds were broadcast planted at the Nutria and Bear Canyon fields. The farmers managing Bear Canyon, Nutria, and Elk fields often intercrop these additional crops with maize, as do other Zuni farmers (Manolescu 1994). Man-

agers of the Pescado field, however, stated that they do not grow watermelon and squash in their field because these crops require too much water.

Weed and pest management. Although these farmers know that weeds can compete with the crop for water and nutrients, weed management is a low priority. No apparent attempt was made to control weeds in the Pescado field. As a result, the Pescado field exhibited severe weed pressure, with pigweed (*Amaranthus* spp.), ragweed (*Ambrosia* spp.), nightshade (*Solanum* spp.), and wild sunflower (*Helianthus annuus* L.) as the common weed species present. These farmers were not concerned about the weeds, and commented that sunflowers "disguise" the maize from crows. Other Zuni farmers also believe that weeds reduce predation by crows (Manolescu 1994). At each of the other fields, occasional hoeing and hand pulling of weeds was done as time and transportation to the fields permitted. Hoeing and hand-weeding were observed in a number of other fields. As the weeds are hoed, soil was sometimes pushed up around the base of maize hills to provide additional support for crop standability against floodwaters and wind. Elk and Bear Canyon fields had minimal weeds, whereas Nutria field exhibited moderate weed pressure throughout the summer. The greater weed pressure at the Nutria field likely resulted from a greater accumulation of weed seeds over more years of cultivation and transport of weed seeds into the field by occasional cattle grazing. Weeds in the Nutria field included pigweed, ragweed, tumbleweed or Russian thistle (*Salsola kali*), and field bindweed (*Convolvulus arvensis* L.); bindweed was particularly prevalent in the lower quarter of the field where cattle more frequently graze after harvests. Maize in weedy sections of fields tended to be somewhat shorter and wilt more readily than in areas or fields having fewer weeds, indicating that weeds competed with maize for available water.

Farmers report that elk (*Cervus elaphus*) and raven (*Corvus corax,* commonly called "crows" by the Zuni) are major maize pests and difficult to control. Some attempt was made to keep elk out of the Elk field (so named because of the prevalence of elk in and around the field) by placing large logs and brush across game trails leading into the field. These measures seemed to be ineffective. Interestingly, elk did not graze on or trample maize in plots delineated by flagging tape in the Elk or other fields, whereas plants in plots outlined with string or outside the plots in the same fields were damaged by elk. Similarly, flagging tape woven through the top wire of fencing effectively reduces the incidence of elk breaking through or going over fencing in Colorado (McAndrews 2001).

Ravens are notorious for pulling up seedlings and eating grain from developing ears. Scarecrows are sometimes placed in fields in attempts to frighten away the ravens. Traditionally, these birds were trapped, killed, and hung in fields to discourage other ravens (Cushing 1974:186–187); a diagram in Cushing (1974: Plate IV) depicts a field with string strung across it and various objects hung on the strings. Although scarecrows and dead ravens were observed in other Zuni fields, these were not erected in any of the fields in this study. However, in an effort to reduce raven damage to developing ears, farmers managing the Elk field strung fishing line above the maize plants between pinyon and juniper trees and poles made from tree branches. They had observed this method at the controlled experiment fields of the larger agroecology study and decided to test it themselves. Because the method effectively deterred raven damage in their field, these

farmers indicated that they would use this approach again. Like other producers, Zuni farmers often experiment with new methods; their production systems are dynamic and evolving.

Insects, pathogens, and other animals were not mentioned by any of the farmers in this study as important pests. Farmers surveyed by Brandt (1992) and Manolescu (1994), however, complained about crop damage caused by small animals and insects, especially grasshoppers (*Melanoplus* spp.).

Plant population density. Plant population density varied widely among fields (Table 5). Measured plant population densities were within the range of densities predicted from the planting information provided by the farmers. With four kernels sown per hill and hills spaced roughly 1.5 to 2.5 m apart equidistantly, a population density of 6,400 to 18,000 plants/ha was expected at the Nutria, Bear Canyon, and Elk fields; actual mean density in these fields was 11,973 plants/ha.

Plant population density is a function of the number of kernels planted per hill, germination and emergence success, and hills per unit land area. The higher population density of the Nutria field resulted from its greater number of hills per plot, 60% greater than in the other fields, and nearly double the mean number of plants per plot of the four fields. Poor seedbed quality, together with the fewer kernels sown per hill, likely account for the relatively sparse population density of the Pescado field; good seed-soil contact is essential for seed uptake of soil moisture for germination.

Plant density among plots within each field was also highly variable, indicating uneven hill and/or kernel distribution, and/or variable germination and stand establishment success. The difference between the planted population and actual stand suggests that emergence among the four fields was about 50%, similar to the emergence success (53%) of Zuni maize observed in the controlled experiment fields (Muenchrath, unpublished data). Lack of moisture, cool soil temperature, poor seed quality, and soil mechanical resistance can impede germination and emergence. Although the plant stand is also sometimes reduced by predation of seedlings, farmers in this study did not comment on any early-season predation and expressed general satisfaction with their stands at mid-summer.

Harvest. Farmers reported that harvest normally occurs in late September or early October, depending on crop maturity, frost, and time, labor and transportation availability. Mature ears and those judged sufficiently mature by the farmers, at least at the milk stage (or approximately R3 in the staging system of Ritchie et al. 1997) were hand harvested. Farmers indicated that immature ears and plant stubble would be used as winter livestock fodder.

Grain Yield.—Grain yield varied among fields, averaging 572.4 kg/ha (± 180.7) (Table 6). Pescado field produced no harvestable grain. Its rough seedbed, poor crop stand, severe weed competition, and predation by elk resulted in few maize plants and no grain by the end of the season. Grain yield across the other three fields averaged 763.2 kg/ha (± 200.3), similar to the 750 kg/ha reported as the common yield produced in Zuni fields in the late nineteenth century (Scott 1893). Nine Zuni fields sampled in 1992 produced a mean yield of 561.2 kg/ha (± 105.7); yield of the six rainfed and runoff fields in that sample averaged 625.7 kg/ha (± 142.5) (Manolescu 1994).

TABLE 6.—Grain yield per plot, per plant, and per hectare, and number of harvestable ears per plant. Standard error of the mean reflects variability among plots within the field. Plots in the Pescado field produced no grain.

	Grain yield per plot (g/plot)		Calculated grain yield per plant (g/plant)		Estimated field grain yield (kg/ha)		Ears per plant	
Field name	Mean	± SE	Mean	± SE	Mean	± SE	Mean	± SE
Bear Canyon	631	199	38.0	10.5	252.2	79.5	1.4	0.4
Nutria	490	56	14.3	2.9	196.1	22.2	0.7	0.1
Elk	4,603	1,407	214.4	64.9	1,841.2	562.7	2.5	0.3
Pescado	0	0	0.0	0.0	0.0	0.0	0.0	0.0
Across Fields:	1,430	452	66.7	21.0	572.4	180.7	1.1	0.2

Other traditional maize grown in the region produce comparable yields. Mean yield of the four Zuni farmers' fields nearly matches the best yield (585.4 kg/ha) of 35 Hopi fields sampled in 1994, a year that was 36 to 57% drier than normal at Hopi (Manolescu 1995); the Hopi fields produced mean yield of 194.3 kg/ha (± 25.9). Current production practices of Hopi and Zuni farmers are similar. Tohono O'odham "60 day" maize grown under a range of moisture regimes in central New Mexico produced mean grain yields of 2140 (± 300) kg/ha in 1992 and 510 (± 160) kg/ha in 1993 (Muenchrath 1995); Tohono O'odham maize is customarily produced in runoff systems on the Papago Indian Reservation, located west of Tucson, Arizona in the Sonoran Desert.

Mean yield of the three productive Zuni fields is also comparable to, and the yield of the Elk field (1841 kg/ha) exceeds, the general productivity of unimproved open-pollinated cultivars. Before the early 1930s and widespread adoption of hybrids produced from improved inbred lines, national U.S. maize yield averaged about 1300 kg/ha (Hallauer et al. 1988; Troyer 1999). For comparison, modern maize hybrids produced commercially in dryland systems of the U.S. Southern Great Plains typically yield 3000 to 4000 kg/ha (Jackson et al. 1983), whereas maize grown in the more humid U.S. Corn Belt (Indiana, Illinois, Iowa, Minnesota, and Nebraska) yields about 8200 kg/ha (calculated from NASS-USDA data, 1990–2000). Commercial production systems commonly use high plant population densities, about 50,000 plants/ha, fertilizer amendments, and pesticides.

Yield differences among farmers' fields reflect differences in conditions. Killing frost before maturity limited yield in the Bear Canyon field; this field was not planted until June 1. Competition among plants, resulting from the relatively high plant population density and moderate weed pressure, likely restricted the yield of the Nutria field. Despite similar inattention, Elk field had few weeds and produced the most grain. The greater productivity of Elk field is attributed to its minimal weed competition, timely planting, multiple and timely runoff events, and short field cropping history. Unlike the other fields in this study, Elk field has no evidence of cultivation prior to 1997; lack of previous cultivation may account for the minimal weed pressure and, with the exception of elk, no other apparent pests. Fields that produce the same crop repeatedly often build up detrimental pest populations. Crop rotations and extended fallow periods can diminish or eliminate such pest problems. Manolescu (1994) noted similar trends

between yield and population density, weed pressure, planting date, and fallow period.

Similar to the relatively high yielding Elk field, the experimental fields had minimal weed pressure and were planted in mid-May. Elk field, however, produced 45% more grain relative to those experimental areas that received runoff plus its sediments and organic debris[3] (1307 kg/ha in 1997 and 1288 kg/ha in 1998 at population densities of 14,222 and 12,889 plants/ha, respectively) (Muenchrath, unpublished data). These yield differences may be due to the amount and timing of the runoff events in the respective fields. In the experimental fields, runoff was applied from three runoff events, all occurring in late July and early August 1997, and from a single event in early August 1998. Elk field had three documented runoff events: in early July, late July, and early August. The Elk field runoff events were ideally timed, shortly preceding and coinciding with the sensitive flowering stage; the four week period bracketing silk emergence is the most critical time in the determination of grain yield (Denmead and Shaw 1960; Shaw 1988). The coarser surface soil texture of Elk field may be a contributing factor, facilitating water infiltration and retention. The high grain yield of Elk field was comparable to the 1998 mean yield across all treatments at the experimental fields, 1886 kg/ha (Muenchrath, unpublished data).

The high yield of Elk field, however, is less than the full yield potential of Zuni maize. Elk field produced less than half of the best yield obtained in the controlled experiment fields, 3829 kg/ha, which was produced in 1997 with synthetic fertilizers and applications of irrigation water as needed (Muenchrath, unpublished data). The higher yield of this treatment is attributable to additional water from the greater rainfall (191 mm) and irrigation, rather than to nutrient inputs. Although leaf P at flowering was greater in this fertilized treatment, grain P and leaf and grain N contents did not differ among treatments. Prior to 1997, one of the experimental fields had been fallow for five to seven years, and the other, where the highest yield was obtained, had been fallow for at least 50 years. Fallowing, as noted by Zuni farmers, is important to maintain field productivity.

Within each of the farmers' fields, grain yield among plots varied widely. The coefficient of variation for yield among plots within a field averaged 77.4% in the three productive farmers' fields (CV range among fields was 35.8 to 99.7%). Coefficients of variation among plots in the three experimental field-years ranged from 27.2 to 75.0% (Muenchrath, unpublished data). High variability within and among fields appears to be the norm. No clear relationships between yield and cultivar type, or between yield and soil properties were observed in the farmers' fields.

Although number of ears per plant is a component of yield, grain yield per plot was only weakly correlated with number of ears per plot (r = 0.60 across all four fields, and r = 0.56 across the three productive fields), indicating that many harvested ears were partially barren. Mean number of ears/plant, 1.1 (± 0.2), was less than that obtained in the experimental fields, 2.1 ears/plant (Muenchrath, unpublished data). The high number of ears per plant in the Elk field, together with its moderate grain yield per ear, resulted in high yields with a modest plant population density. The relatively high density and weeds in the Nutria field likely suppressed the number of ears produced per plant. The number of har-

vestable ears per plot also varied among fields and among plots within fields, averaging 33.7 ears/plot (± 3.5) or an estimated 10,120 ears/ha (± 1530) across all four of the farmers' fields (Table 6). Ear prolificacy contributes to yield stability by minimizing the likelihood of barrenness in stressful environments, and augments yield under more favorable conditions (Hallauer and Troyer 1972).

Yield reflects the compounded, cumulative effects of growth and development in response to management and the environment over the entire growing season. Grain yield derives from several components: the number of plants per unit land area, number of ears per plant, number of kernels per ear, and weight per kernel. Temperature, water, nutrient, pests, or other stresses can cause reduced emergence and plant stand, development of fewer ears or ovules, poor pollination and barrenness, and/or restricted grain fill, limiting ultimate yield. The impact of a stress depends on the prior condition of the crop and the severity, timing, and duration of the stress. Various stressors influenced the productivity of these farmers' fields.

CONCLUSIONS

While maintaining traditional elements of their agricultural strategies, Zuni farmers adapt and innovate in response to their dynamic environment. Zuni farmers continue to select field sites that are likely to have a sufficiently long growing season and receive runoff flows, exhibit desirable soil texture and native vegetation qualities, and where they have use rights. At Zuni, temperature and precipitation are highly variable from place to place, even within the same farming district, and from year to year. Although the production practices observed in this study varied somewhat among fields, management differences do not appear to be directly related to environmental differences among the fields. Nevertheless, we think that the general strategy of using geographically diverse fields would improve the chances of obtaining some successful production. The extensive production system of fields situated in many different niches likely contributed importantly to the long-term agricultural stability of Zuni and other traditional communities throughout the region.

Yield varied widely among the farmers' fields, including among the three managed by a single farmer and his family. Yield differences are attributed to differences among farmer management practices and influenced by field cropping history and seasonal environmental factors. Because moisture and nutrients were generally adequate in these farmers' fields, planting date and weed pressure likely had the greatest impact on grain yield in 1998. With average moisture and temperatures, greater yield potential could be realized in these runoff systems with timely planting and more intensive management of periodically fallowed fields. The level of management these farmers are able to expend on maize production, however, is restricted by availability of time, labor, equipment, and transportation. Despite these constraints, these and other Zuni farmers persist, largely because of the cultural value and tradition of maize and farming in Zuni life (Cleveland et al. 1995; Manolescu 1994). Challenges faced by individual Zuni and tribal efforts, such as the Zuni Sustainable Agriculture Program, to sustain agriculture as a lifeway and economic activity parallel those in other sectors of U.S. agriculture, where farmers also increasingly struggle with the competing time and resource

demands of farming and economically necessary off-farm jobs (Cleveland et al. 1995; Heller and Keoleian 2000; Hoppe et al. 2001).

To better understand the function, structure, and longevity of Zuni and other traditional runoff agricultural systems in the area, and to develop sustainable systems suitable for arid and semiarid zones, longer-term studies of a larger sample of farmers' fields and practices, continued multidisciplinary agroecological research, and agronomic evaluation of the associated cultivars are needed.

NOTES

[1] Carl S. White, Dept. of Biology, University of New Mexico, Albuquerque.

[2] Carol Brandt, New Mexico Alliance for Graduate Education & the Professoriate, Office of Graduate Studies, University of New Mexico, Albuquerque.

[3] Treatments in the controlled cropping experiment of the larger agroecology study tested the effects of different runoff components on maize productivity, specifically the effects of moisture and nutrients delivered by storm flows. Treatments were randomly assigned to plots in each field in a complete, randomized block design, with three replications in each field. The five treatments were

- Rainfed—Direct rain only;
- Runoff water—Liquid portion of runoff (water plus dissolved and suspended components) applied within 2 to 7 days of runoff event from the catchment installed above the field;
- Runoff with sediments—Liquid and solid runoff components (water, solutes, organic materials, and sediments) applied to match the above treatment application volume and timing;
- Irrigation water—Irrigation water from local reservoirs applied to match runoff application volume and timing; and
- Irrigation water with fertilizer—Irrigation water plus synthetic N and P applied as needed by the crop to avoid water-deficit stress. First application contained 101 kg N/ha and 36 kg P/ha and the next application added 77 kg N/ha, for total seasonal fertilizer application of 178, 36, and 0 kg/ha N, P, and K, respectively; K was not limiting.

Locally produced Zuni blue maize seed was soaked overnight before planting, and hand planted 13–15 May 1998 at 15 cm depth in clusters of four kernels each, spaced equidistantly 1.5 m apart. Frequent hoeing controlled weeds. Fencing kept elk and other pests out of the fields. Fishing line strung in a grid across the top of the field protected the crop from bird predation.

ACKNOWLEDGMENTS

The cooperation and gracious generosity of Wilmer Quandelacy and his family, and Stanley Sanchez and Carmichael Laiwakete are gratefully acknowledged. The assistance of the Zuni Sustainable Agriculture and Conservation Projects, and members of the agroecology research team were essential to this project. Carl White and Chris Thomas, University of New Mexico, provided precipitation, temperature, and nitrogen mineralization data. Jennifer Nelson and Jamie Patton, Iowa State University Pedometrics Laboratory, assisted with particle-size analyses. The comments and suggestions of Carol Brandt and

Kathleen Manolescu, who kindly reviewed an early draft of the manuscript, are greatly appreciated.

This material is based upon work supported by the National Science Foundation under Grant No. 9528458. Journal Paper No. J-19205 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 3666, and supported by Hatch Act and State of Iowa.

REFERENCES CITED

Abdul-Jabbar, A.S., J.W. Sammis, D.G. Lugg, C.E. Kallsen, and D. Smeal. 1983. Water use by alfalfa, maize, and barley as influenced by available soil water. *Agricultural Water Management* 6:351–363.

Anaya Garduño, Manuel. 1992. Captación de lluvia en zonas áridas y semiáridas. Ingenieria Agronómica, Colegio de Ingenieros Agrónomos de México. Noviembre-Diciembre:23–31.

Balling, Jr., Robert C. and Stephen G. Wells. 1990. Historical rainfall patterns and arroyo activity within the Zuni River drainage basin, New Mexico. *Annals of the Association of American Geographers* 80(4):603–617.

Biggar, H. Howard. 1918. The old and new in corn culture. *Yearbook of the Department of Agriculture* No. 776. U.S. Government Printing Office, Washington D.C.

Bohrer, Vorsila L. 1960. Zuni agriculture. *El Palacio* 67:181–202.

Bradfield, Maitland. 1971. *The Changing Pattern of Hopi Agriculture.* Occasional Paper 30, Royal Anthropological Institute of Great Britain and Ireland, London.

Brady, Nyle C. and Ray R. Weil. 2002. *The Nature and Properties of Soils,* 13th ed. Prentice-Hall, Upper Saddle River, New Jersey.

Brandt, Carol B. 1992. *Sustaining Traditional Crops of the Zuni Pueblo Indians of West-central New Mexico: A Harvest for the Local and Global Agricultural Community.* Ethnobiological Technical Series Paper No. 92-8. Zuni Heritage and Historic Preservation Office, Zuni, New Mexico.

———. 1995. Traditional agriculture on the Zuni Indian Reservation in the recent historic period. In *Soil, Water, Biology, and Belief in Prehistoric and Traditional Southwestern Agriculture,* ed. H. Wolcott Toll, pp. 291–301. Special Publication No. 2, New Mexico Archaeological Council, Albuquerque.

Bruins, H.J., M. Evenari, and U. Nessler. 1986. Rainwater-harvesting agriculture for food production in arid zones: the challenge of the African famine. *Applied Geography* 6:13–32.

Bryan, K. 1929. Flood-water farming. *The Geographical Review* 19:444–456.

Castetter, Edward F. and Willis H. Bell. 1942. *Pima and Papago Indian Agriculture.* University of New Mexico Press, Albuquerque.

Cihacek, Larry, Charles Glover, Estaban Herrara, and Fred Widmoyer. 1992. *Guide A-122: Soil Test Interpretations.* New Mexico State University, Las Cruces.

Cleveland, David A., Fred Bowannie, Jr., Donald F. Eriacho, Andrew Laahty, and Eric Perramond. 1995. Zuni farming and United States government policy: the politics of biological and cultural diversity in agriculture. *Agriculture and Human Values* 12(3):2–18.

Collins, G.N. 1914. A drought-resisting adaptation in seedlings of Hopi maize. *Journal of Agricultural Research* 1(4):293–306.

Critchley, Will and Klaus Siegert. 1991. Water harvesting: a manual for the design and construction of water harvesting schemes for plant production(AGL/MISC/17/91) [Online]. Available at http:www.fao.org/docrep/U3160E/u3160e00.htm (verified 13 November 2001).

Cushing, Frank Hamilton. 1974. *Zuni Breadstuff.* Originally published 1920. Indian Notes and Monographs, vol. 2. Museum of the American Indian, Heye Foundation, New York.

Damp, J.E., S.A. Hall, and S. Smith. 2002. Early irrigation on the Colorado Plateau near Zuni Pueblo, New Mexico. *American Antiquity,* in press.

Denmead, O.T. and R.H. Shaw. 1960. The

effects of soil moisture stress at different stages of growth on the development and yield of corn. *Agronomy Journal* 52:272–274.

Doerge, T.A. 1985. *A Summary of Soil Test Information for Arizona's Surface Agricultural Soils: 1965–1984.* Department of Soil and Water Science, University of Arizona, Tucson.

Doolittle, William. 2000. *Cultivated Landscapes of North America.* Oxford University Press, New York.

FAO (Food and Agriculture Organization of the United Nations). 2000. Crops and drops: making the best use of land and water [Online]. Available at ftp://ftp.fao.org/agl/aglw/docs/cropdrop.pdf (verified 13 November 2001).

Ferguson, T.J. 1985. Patterns of land use and environmental change on the Zuni Indian Reservation, 1846–1985: ethnohistorical and archaeological evidence. Plaintiff's Exhibit 6000. Expert testimony submitted to the United States Claims Court as evidence in the case of Zuni Indian Tribe v. United States, Docket 327-81L. September 30, 1985.

———. 1996. *Historic Zuni Architecture and Society.* University of Arizona Press, Tucson.

Ferguson, T.J. and E. Richard Hart. 1985. *A Zuni Atlas.* University of Oklahoma Press, Norman.

Ford, Richard I. 1985. Zuni land use and damage to Trust land, Plaintiff's Exhibit 7000. Expert testimony submitted to the United States Claims Court as evidence in the of case Zuni Indian Tribe v. United States, Docket 327-81L. 15 August 1985.

Gleick, Peter H. 2000. Water: the potential consequences of climate variability and change for the water resources of the United States [Online]. Available at http://www.gcrio.org/NationalAssessment/water/water.pdf (verified 13 November 2001).

Graham, Martha. 1990. Report on documented twentieth century irrigated agricultural fields on the Zuni Indian Reservation. Submitted to the Institute for the North American West, Seattle WA. Manuscript on file, Zuni Heritage and Historic Preservation Office, Zuni, New Mexico.

Hack, J.T. 1942. *The Changing Physical Environment of the Hopi Indians of Arizona.* Harvard University Press, Cambridge, Massachusetts.

Hallauer, A.R., Wilbert A. Russell, and K.R. Lamkey. 1988. Corn breeding. In *Corn and Corn Improvement,* 3rd ed., eds. G.F. Sprague and J.W. Dudley, pp. 463–564. Agronomy Monograph 18, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Hallauer, A.R. and A.F. Troyer. 1972. Prolific corn hybrids and minimizing risk of stress. In *Proceedings of the 27th Annual Corn and Sorghum Research Conference, Chicago, IL, 12–14 December,* pp. 140–158. American Seed Trade Association, Washington D.C.

Hammond, G.P. and A. Rey, eds. 1940. *Narratives of the Coronado Expedition.* University of New Mexico Press, Albuquerque.

Hart, E. Richard, ed. 1995. *Zuni and the Courts: A Struggle for Sovereign Land Rights.* University Press of Kansas, Lawrence.

Havener, Celeste Illgner. 1999. The Influence of Zuni Runoff Agriculture on Microbial Populations in Cultivated Fields. M.S. Thesis (Renewable Resources), University of Wyoming, Laramie.

Havener, C.I., J.B. Norton, and S.E. Williams. 1999. Nutrient contribution to Zuni runoff agricultural fields of watershed vegetation and soils. In *1999 Agronomy Abstracts,* p. 44. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison Wisconsin.

Heller, Martin C. and Gregory A. Keoleian. 2000. Life cycle-based sustainability indicators for assessment of the U.S. food system. Report No. CSS00–04, Center for Sustainable Systems, University of Michigan, Ann Arbor [Online]. Available at: http://css.snre.umich.edu/css_doc/CSS_2000_4.pdf (verified 7 November 2001).

Homburg, Jeffrey Allan. 2000. Anthropogenic Influences on American Indian Agricultural Soils of the Southwestern United States. Ph.D. Dissertation (Agronomy), Iowa State University, Ames (Dissertation Abstracts International No. DAI-B 61/02).

Hoppe, Robert A., James Johnson, Janet E.

Perry, Penni Korb, Judith E. Sommer, James T. Ryan, Roger C. Green, Ron Durst, and James Monke. 2001. Structural and Financial Characteristics of U.S. Farms: 2001 Family Farm Report. USDA-ERS Agriculture Information Bulletin No. 768 [Online]. Available at: http://www.ers.usda.gov/Publications/aib768/ (verified 7 November 2001).

Jackson, T.L., A.D. Halvorson, and B.B. Tucker. 1983. Soil fertility in dryland agriculture. In *Dryland Agriculture,* eds. H.E. Dregene and W.O. Willis, pp. 297–332. Agronomy Monograph 23, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Khalil, Samina, Thomas E. Loynachan, and M. Ali Tabatabai. 1994. Mycorrhizal dependency and nutrient uptake by improved and unimproved corn and soybean cultivars. *Agronomy Journal* 86: 949–958.

Kintigh, K.W. 1985. *Settlement, Subsistence, and Society in Late Zuni Prehistory.* Anthropological Papers of the University of Arizona, no. 44. University of Arizona Press, Tucson.

Klemmedson, J.O. 1989. Soil organic matter in arid and semiarid ecosystems: sources, accumulation, and distribution. *Arid Soil Research and Rehabilitation* 3:99–114.

Klute, A., ed. 1986. *Methods of Soil Analysis. Physical and Mineralogical Methods,* 2nd ed. Monograph 9, part 1. American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin.

Ludwig, J.A. 1987. Primary productivity in arid lands: myths and realities. *Journal of Arid Environments* 13:1–7.

McAndrews, Gina M. 2001. Evaluation of a Participatory Approach to Mediate Conflict between Wildlife and Livestock Interests. Ph.D. Dissertation (Agronomy), Iowa State University, Ames.

Manolescu, Kathleen. 1994. The culture of Zuni land technologies: an appendix for the Zuni Development Plan, Pueblo of Zuni and Zuni Conservation Project. Report on file, Zuni Conservation Program, Blackrock, New Mexico

———. 1995. Hopi corn production. A report on research conducted for the Bureau of Indian Affairs. Report on file, Bureau of Indian Affairs, Phoenix area office, Phoenix, Arizona.

Maxwell, Timothy D. 2000. Looking for Adaptation: A Comparative and Engineering Analysis of Prehistoric Agricultural Technologies and Techniques in the Southwest. Ph.D. Dissertation (Anthropology), University of New Mexico, Albuquerque.

Metting, B. 1991. Biological surface features of semiarid lands and deserts. In *Semiarid Lands and Deserts: Soil Resource and Reclamation,* ed. J. Skujins, pp. 257–293. Marcel Dekker, New York.

Muenchrath, Deborah Ann. 1995. Productivity, Morphology, Phenology, and Physiology of a Desert-adapted Native American Maize (*Zea mays* L.) Cultivar. Ph.D. Dissertation (Agronomy), Iowa State University, Ames (Dissertation Abstract No. 95–40927).

Nabhan, Gary P. 1984. Soil fertility renewal and water harvesting in Sonoran Desert agriculture: the Papago example. *Arid Lands Newsletter* 20:21–28.

Norton, Jay B. 1996. Soil, Geomorphic, and Ecological Factors in Zuni Runoff Agriculture. M.S. Thesis (Agronomy), Iowa State University, Ames.

———. 2000. Agroecology, Hydrology, and Conservation of Ephemeral Streams and Alluvial Fans, Zuni Pueblo, New Mexico. Ph.D. Dissertation (Forestry), University of Montana, Missoula.

Norton, J.B. and A.H. Laahty. 1999. Traditional Zuni landscape stability and soil fertility renewal. In *1999 Agronomy Abstracts,* p. 44. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Norton, J.B., R.R. Pawluk, and J.A. Sandor. 1998. Observation and experience linking science and indigenous knowledge at Zuni, New Mexico. *Journal of Arid Environments* 39:331–340.

Olson, R.A. and D.H. Sander. 1988. Corn production. In *Corn and Corn Improvement,* 3rd ed., eds. G.F. Sprague and J.W. Dudley, pp. 639–686. Agronomy Monograph 18, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Orr, B.R. 1987. *Water Resources of the Zuni Tribal Lands, McKinley and Cibola Counties, New Mexico.* U.S. Geological Survey, Denver, Colorado.

Osborn, H.B. and K.G. Renard. 1970. Thunderstorm runoff on the Walnut Gulch Experimental Watershed, Arizona, USA. *International Association of Scientific Hydrology* 96:455–464.

OTA (Office of Technology Assessment). 1983. *Water-related Technologies for Sustainable Agriculture in U.S. Arid/Semiarid Lands.* U.S. Congress, Office of Technology Assessment Document F-212, Oct. 1983. Washington D.C.

Page A.L., R.H. Miller, and D.R. Keeney, eds. 1982. *Methods of Soil Analysis. Chemical and Microbiological Properties,* 2nd ed. Monograph no. 9, part 2. American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin.

Pawluk, Roman R. 1995. Indigenous Knowledge of Soil and Agriculture at Zuni Pueblo, New Mexico. M.S. and M.A. Thesis (Agronomy and Anthropology), Iowa State University, Ames.

Prevost, D.J., R.L. Ahrens, and D.M. Kriz. 1984. Traditional Hopi agricultural methods. *Journal of Soil and Water Conservation* 39:170–171.

Prevost, D.J., Fred Bowannie, Jr., and Andrew Laahty. 1993. Soils in Zuni rainfall runoff fields. *Zuni Farming for Today and Tomorrow* 2 (Summer):8–9. (Occasional newsletter of the Zuni Sustainable Agriculture Project and the Zuni Folk Varieties Project, Zuni NM).

Rhoads, F.M. and J.M. Bennett. 1990. Corn. In *Irrigation of Agricultural Crops,* eds. B.A. Stewart and D.R. Nielsen, pp. 569–596. Agronomy Monograph 30, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Rhoads, F.M. and C.D. Yonts. 1984. Irrigation Scheduling for Corn—Why and How [Online]. National Corn Handbook, Publication NCH-20. Purdue University Cooperative Extension Service. Available at http://www.agcom.purdue.edu/AgCom/Pubs/NCH/NCH-20.html (verified 13 November 2001).

Rhode, David. 1990. Agriculture and water use before the Twentieth Century on the Zuni Reservation, west-central New Mexico. Submitted to the Institute for the North American West, Seattle WA. Manuscript on file, Zuni Heritage and Historic Preservation Office, Zuni NM.

———. 1995. Estimating agricultural carrying capacity in the Zuni region, west-central New Mexico: a water allocation model. In *Soil, Water, Biology, and Belief in Prehistoric and Traditional Southwestern Agriculture,* ed. H. Wolcott Toll, pp. 85–100. Special Publication No. 2, New Mexico Archaeological Council, Albuquerque.

Ritchie, Steven W., John J. Hanway, and Garren O. Benson. 1997. How a Corn Plant Develops. Special Report No. 48. Iowa State University Cooperative Extension Service, Ames.

Sandor, Jonathan A. 1995. Searching soil for clues about Southwest prehistoric agriculture. In *Soil, Water, Biology, and Belief in Prehistoric and Traditional Southwestern Agriculture,* ed. H. Wolcott Toll, pp. 119–137. Special Publication No. 2, New Mexico Archaeological Council, Albuquerque.

Sandor, Jonathan A. and P.L. Gersper. 1988. Evaluation of soil fertility in some prehistoric agricultural terraces in New Mexico. *Agronomy Journal* 80:846–850.

Sandor, J.A., J.B. Norton, D.A. Muenchrath, C.S. White, S.E. Williams, M.D. Ankeny, C.I. Havener, J.A. Homburg, P.D. Stahl, and C.J. Thomas. 1999. Soil, crop, and ecosystem studies of Native American runoff agriculture. In *1999 Agronomy Abstracts,* p. 38. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Scott, Julian. 1893. Pueblos of Laguna, Acoma, and Zuni. In *Extra Census Bulletin: Moqui Pueblo Indians of Arizona and Pueblo Indians of New Mexico, Eleventh Census of the United States,* eds. Thomas Donaldson, expert special agent, and Robert P. Porter, superintendent, pp. 121–131. United States Census Printing Office, Washington D.C.

Shaw, Robert H. 1988. Climate requirement. In *Corn and Corn Improvement,* 3rd ed., eds. G.F. Sprague and J.W. Dudley, pp. 609–638. Agronomy Monograph 18, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Shreve, F. 1934. Rainfall, runoff, and soil moisture under desert conditions. *An-*

nals of the Association of American Geographers 24(3):131–156.

Sitgreaves, L. 1853. Report of expedition down the Zuni and Colorado Rivers in 1851. Executive Document 59, 32nd Congress, 2nd Session. Washington D.C.

Soil Survey Staff. 1993. *Soil Survey Manual,* USDA Handbook 18, 2nd ed. U.S. Government Printing Office, Washington D.C.

———. 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys, USDA Agricultural Handbook 436, 2nd edition [Online]. Available at http://www.statlab.iastate.edu/soils/nssc/ (verified 4 October 2001).

Troyer, A. Forrest. 1999. Background of U.S. hybrid corn. *Crop Science* 39:601–626.

Tuan, Yi-Fu, Cyril E. Everard, Jerold G. Widdison, and Iven Bennett. 1973. *The Climate of New Mexico,* rev. ed. State Planning Office, Santa Fe, New Mexico.

USDA-NRCS, pending. *Soil Survey of McKinley County, New Mexico.* U.S. Government Printing Office, Washington D.C.

Van West, Carla R. 1996. Chapter 17. The heuristic value of estimates of prehistoric agricultural production: a case study from southwestern Colorado. In *Interpreting Southwestern Diversity: Underlying Principles and Overarching Patterns,* eds. Paul R. Fish and J. Jefferson Reid, pp. 133–145. Anthropological Research Papers no. 48, Arizona State University, Tempe.

Waters, M. R. 1992. *Principles of Geoarchaeology: A North American Perspective.* University of Arizona Press, Tucson.

West, N. E. 1991. Nutrient cycling in soils of semiarid and arid regions. In *Semiarid Lands and Deserts: Soil Resource and Reclamation,* ed. J. Skujins, pp. 295–332. Mercel Dekker, New York.

White, C.S., and C.J. Thomas. 1999. Nitrogen contributions from precipitation to a corn field at Zuni, New Mexico. In *1999 Agronomy Abstracts,* p. 40. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, Wisconsin.

Will, George F. and George E. Hyde. 1917. *Corn Among the Indians of the Upper Missouri.* Originally published 1910. University of Nebraska Press, Lincoln.

Wilson, Gilbert L. 1987. *Buffalo Bird Woman's Garden: Agriculture of the Hidatsa Indians.* Minnesota Historical Society Press, St. Paul.

Worster, D. 1985. *Rivers of Empire: Water, Aridity, and the Growth of the American West.* Pantheon Books/Random House, New York.